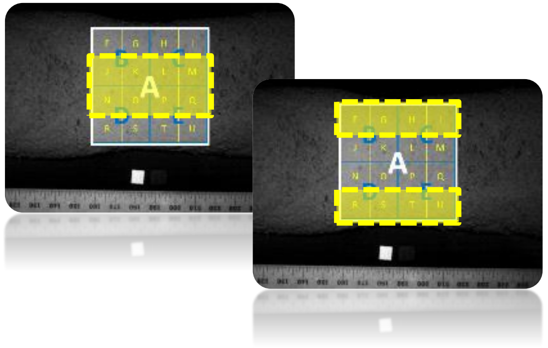
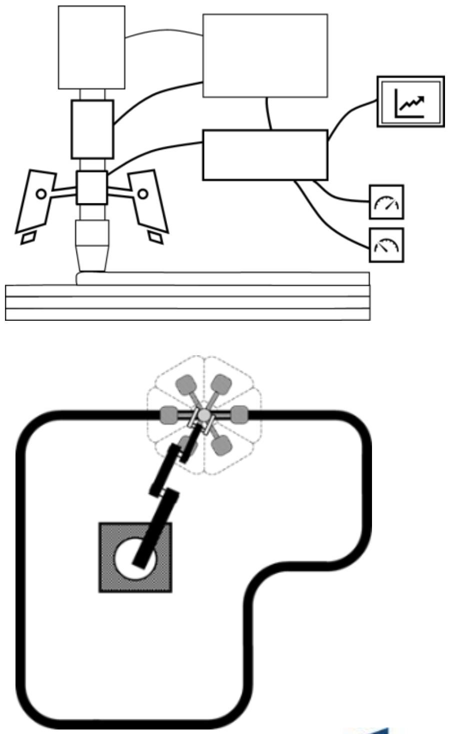
# Computer Vision to Predict Interlayer Bond Strength from Early-Age Properties


## Rakesh Anthony Khan, P.E.

# Using Computer Vision to Predict Interlayer Bond Strength from Early-Age Properties





Primer

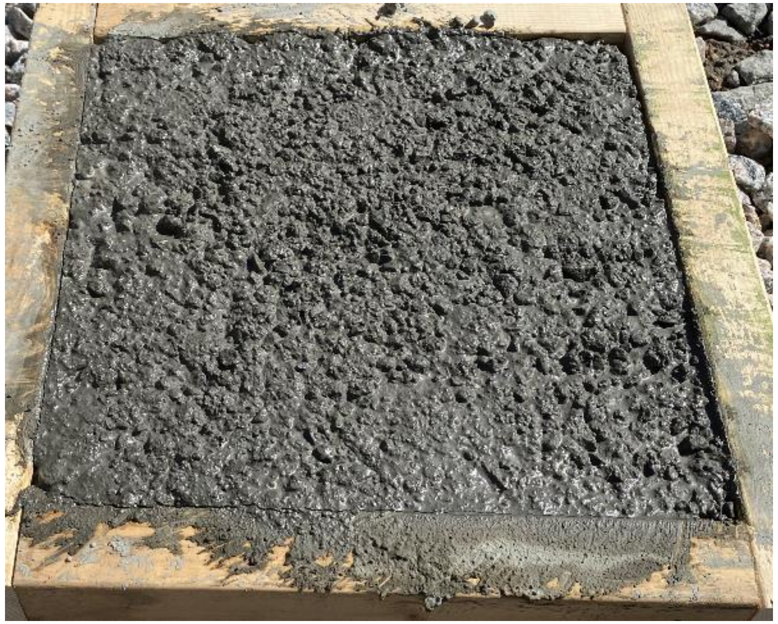
Recent Research

Ongoing Research

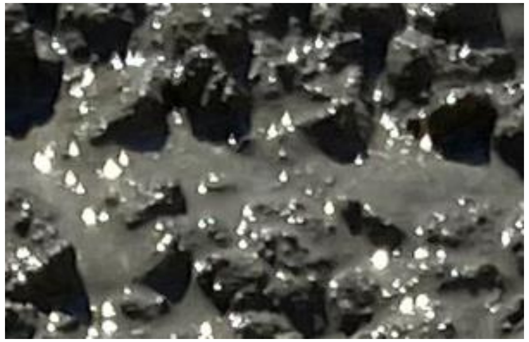
Roadmap

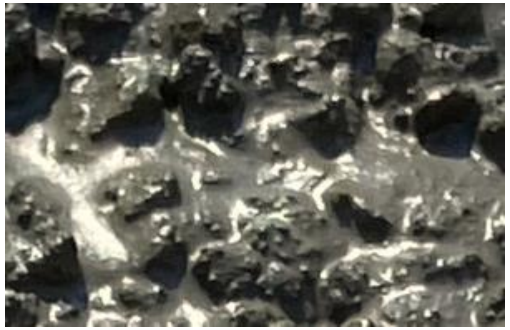
VISION SETTING BONDING FUTURE

Image Adapted from: https://www.okonomikitchen.com/wp-content/uploads/2023/02/banana-ripeness-for-banana-bread-1024x1536.jpg

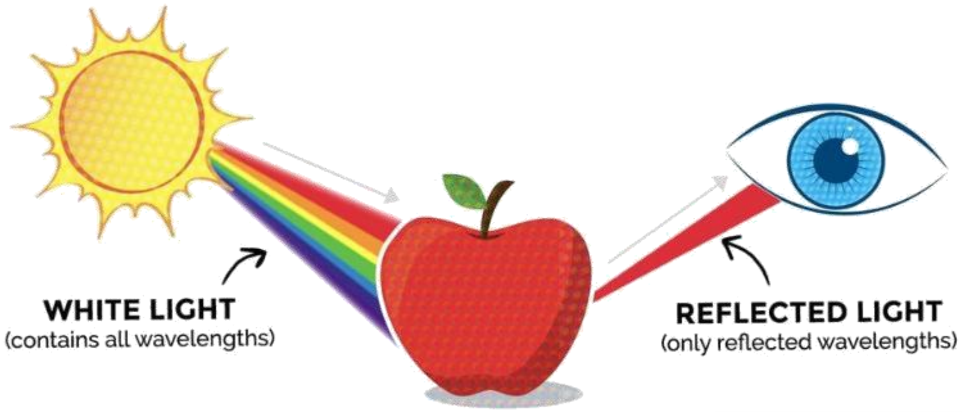





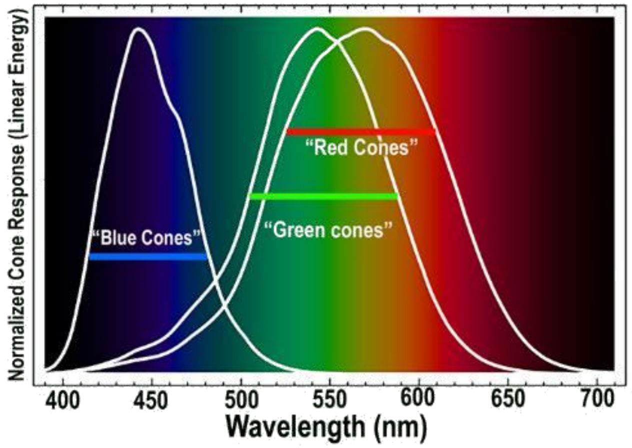




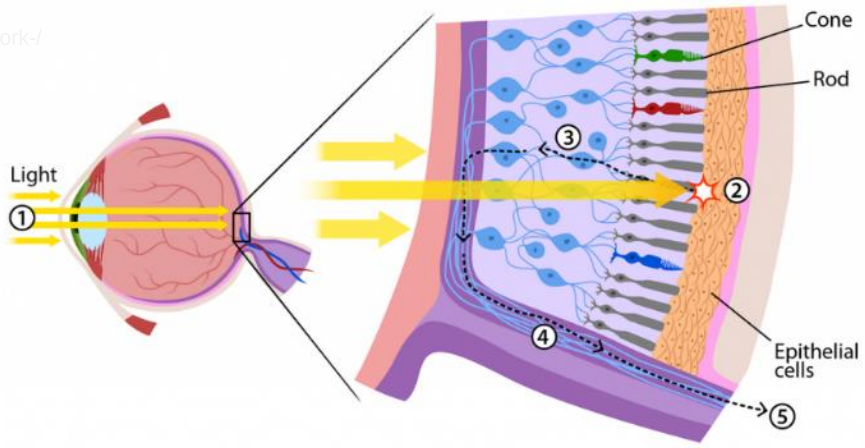
# Human Vision



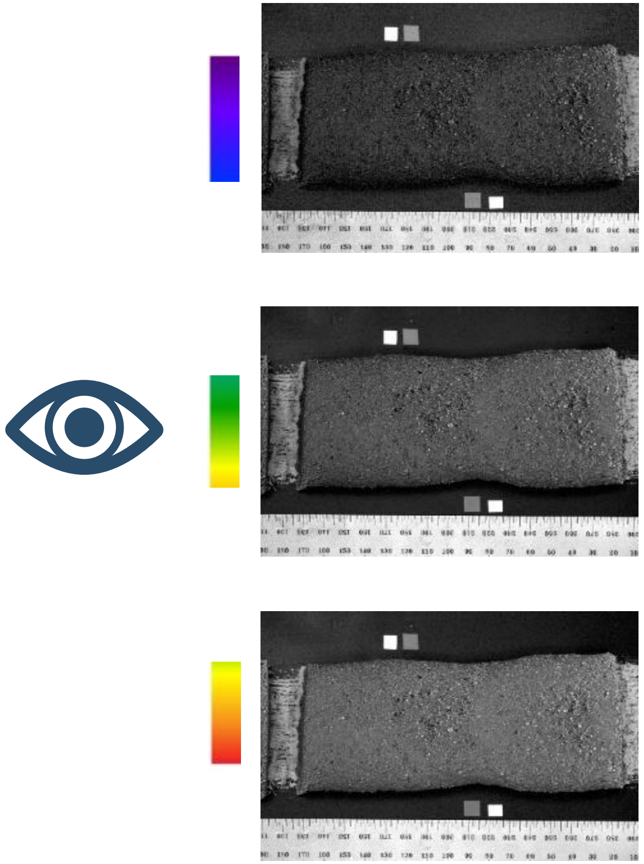

https://www.instructables.com/How-Actually-Colors-Work-/




https://pace.oceansciences.org/color_determination.cgi



# Human ‘Post Processing’



VISION SETTING BONDING FUTURE

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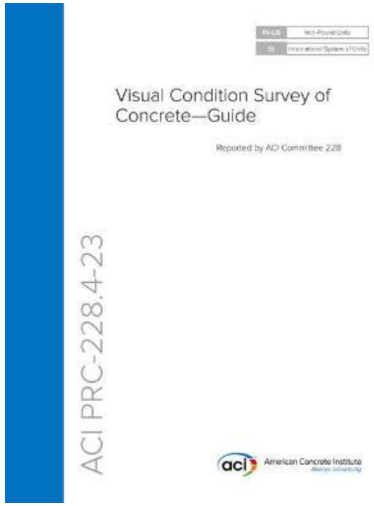
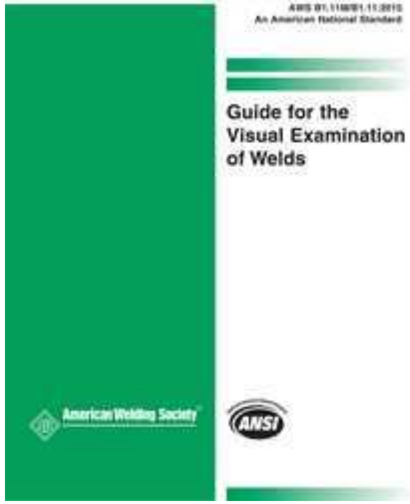
# Visual Inspection

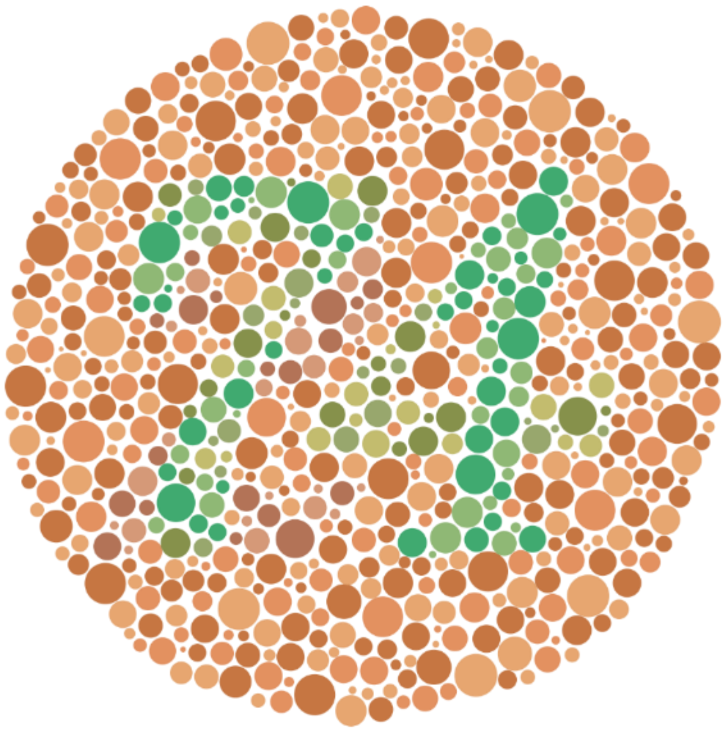
| Concrete | Soil | Lumber | Welds |
|---|---|---|---|
| ACI PRC-228.4-23 | ASTM D2488-17e1 | ASTM D1990-16 | AWS B1.11:2015 |



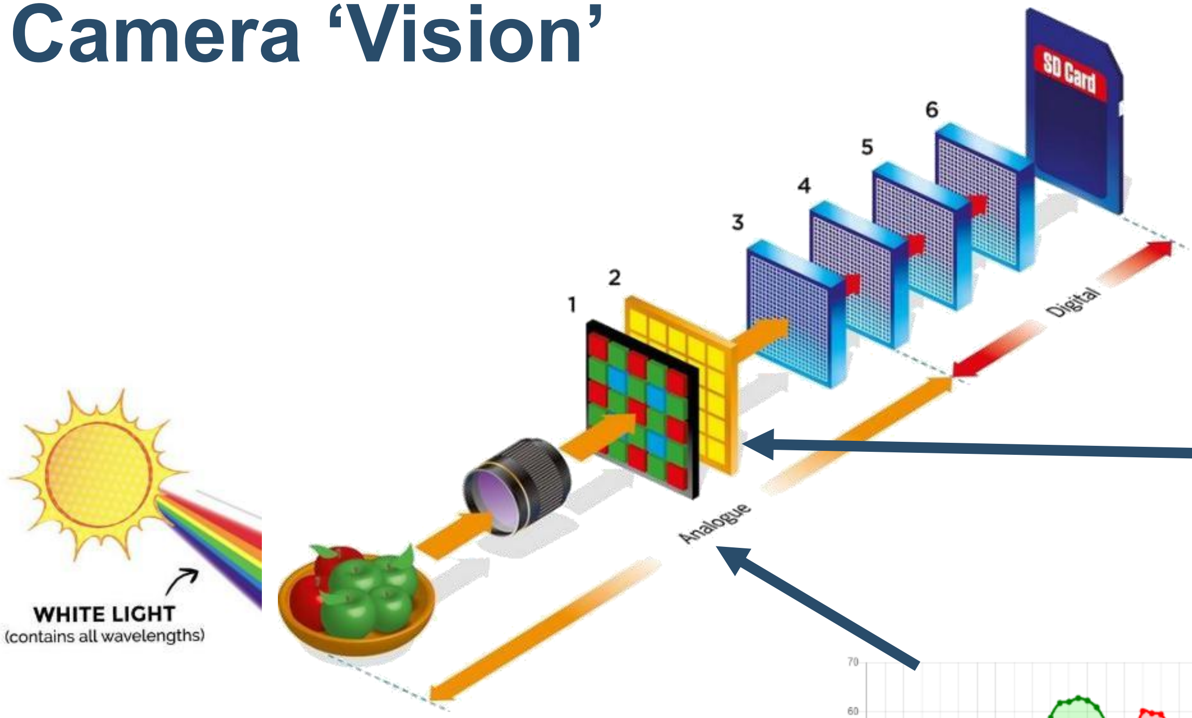


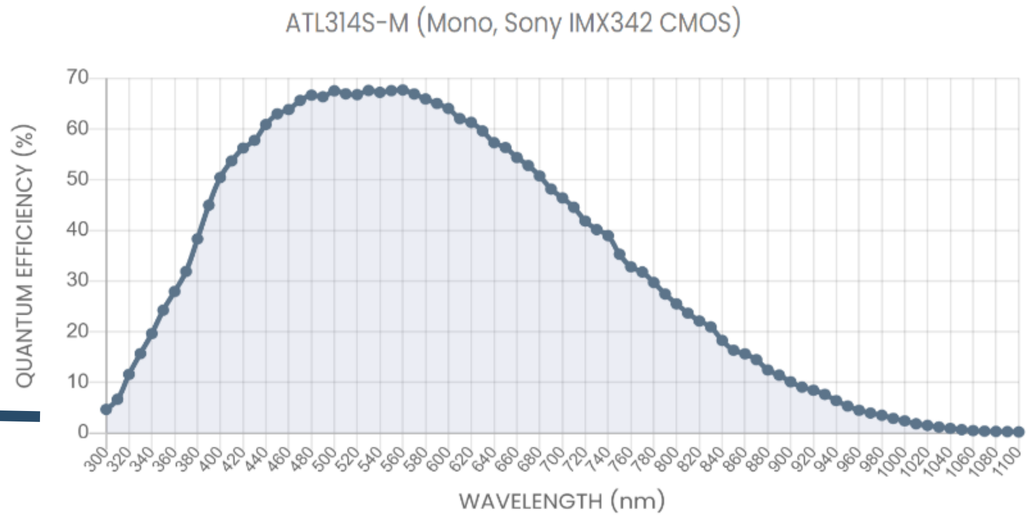
# Operator Variability

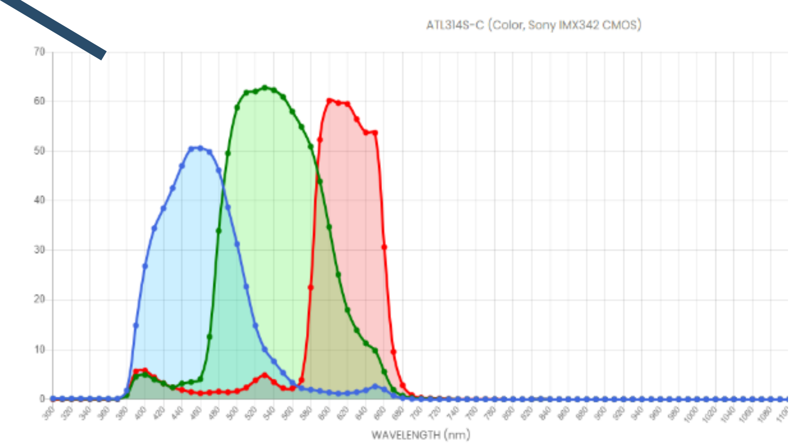


# Camera ‘Vision’

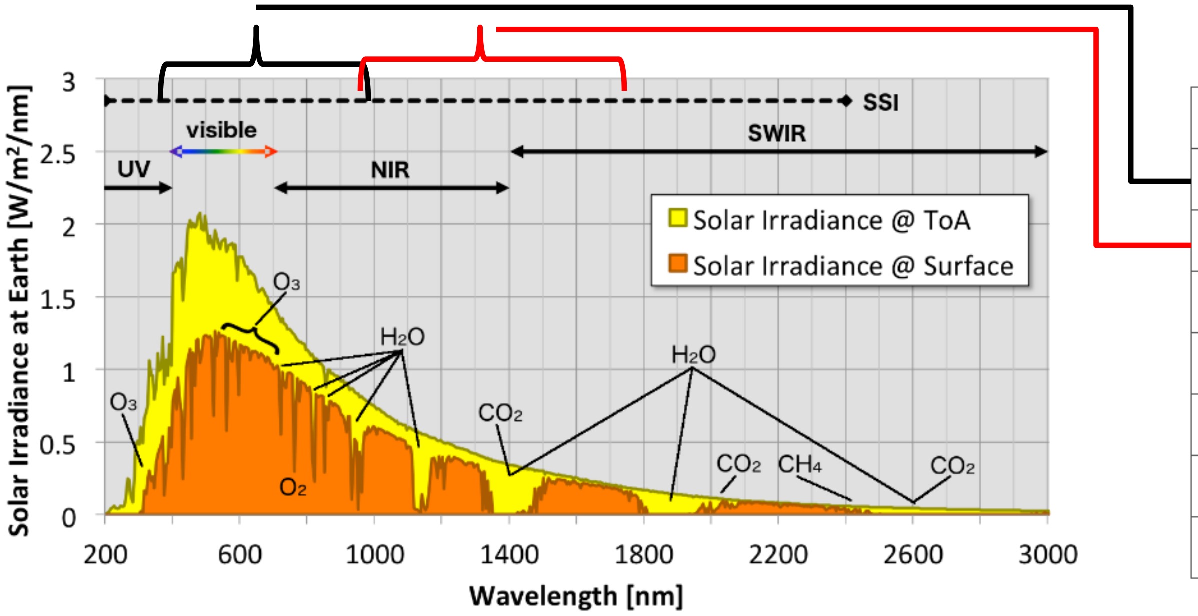



https://www.canon-europe.com/pro/infobank/image-sensors-explained/



# What reflected light can a camera detect that we can't?

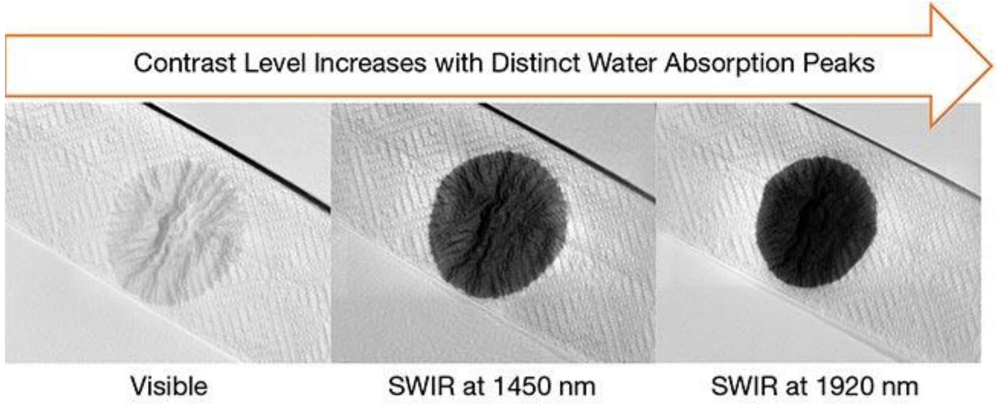



https://sunclimate.gsfc.nasa.gov/article/solar-irradiance

| Detector Material | | Typical VIS-IR Detection Range |
|---|---|---|
| Si | Silicon | 300 nm - 1.0 µm |
| InGaAs | Indium Gallium Arsenide | 900 nm - 1.7 µm |
| Ge | Germanium | 800 nm - 1.6 µm |
| PbS | Lead Sulfide | 1 µm - 2.8 µm |
| PbSe | Lead Selenide | 1 µm - 4.5 µm |
| InSb | Indium Antimonide | 2 µm - 5 µm |
| HgCdTe (MCT) | Mercury Cadmium Telluride | 2 µm - 14 µm |

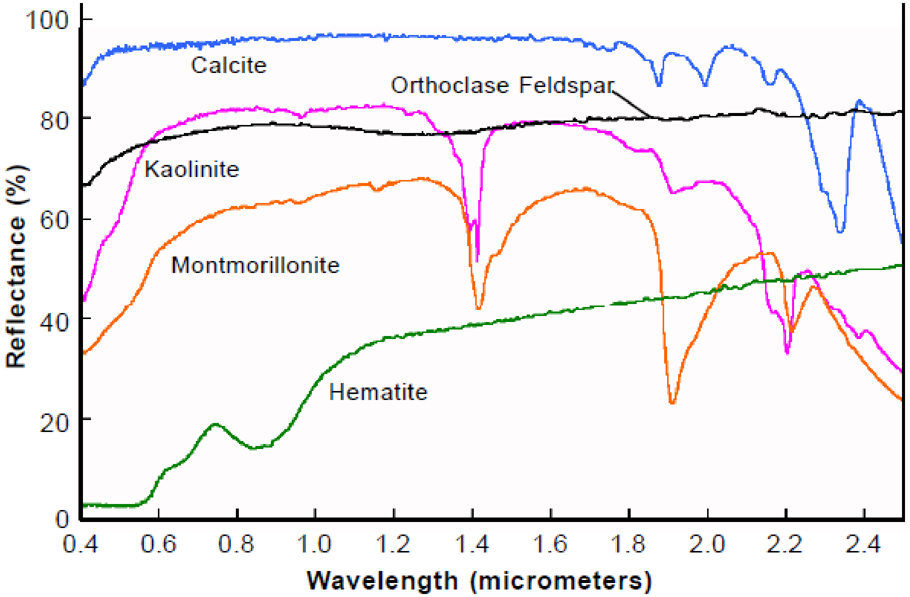
https://quantum-solutions.com/blog/quantum-dot-vis-nir-cameras/

# What is there to see beyond the ‘visible’ range?



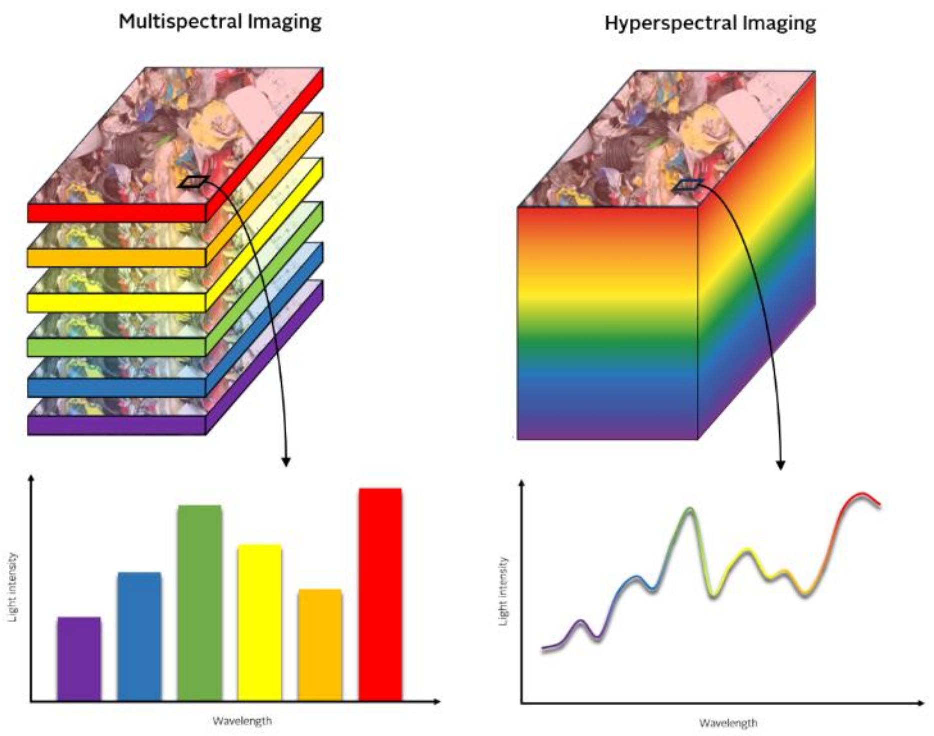

Water absorption peak shows highest contrast at 1920 nm, enabling contrast differentiation and reduction of false defect counts.

https://www.photonics.com/Articles/New_Sensor_Materials_and_Designs_Deepen_SWIR/a68543

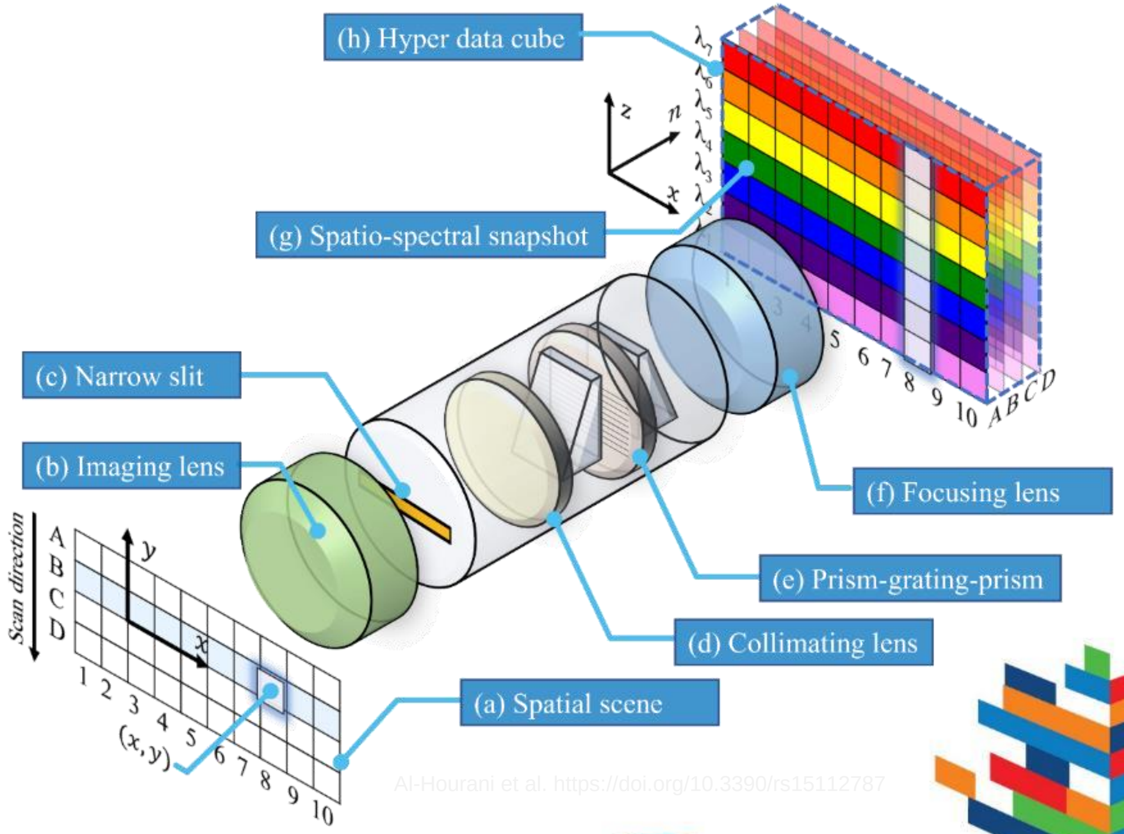



https://www.microimages.com/documentation/Tutorials/hyprspec.pdf

# Multispectral Imaging and Hyperspectral Imaging




https://www.alliedvision.com/en/applications/infrared-hyperspectral-imaging/spectral-imaging/




Al-Hourani et al. https://doi.org/10.3390/rs15112787

# Hardened Concrete in SWIR

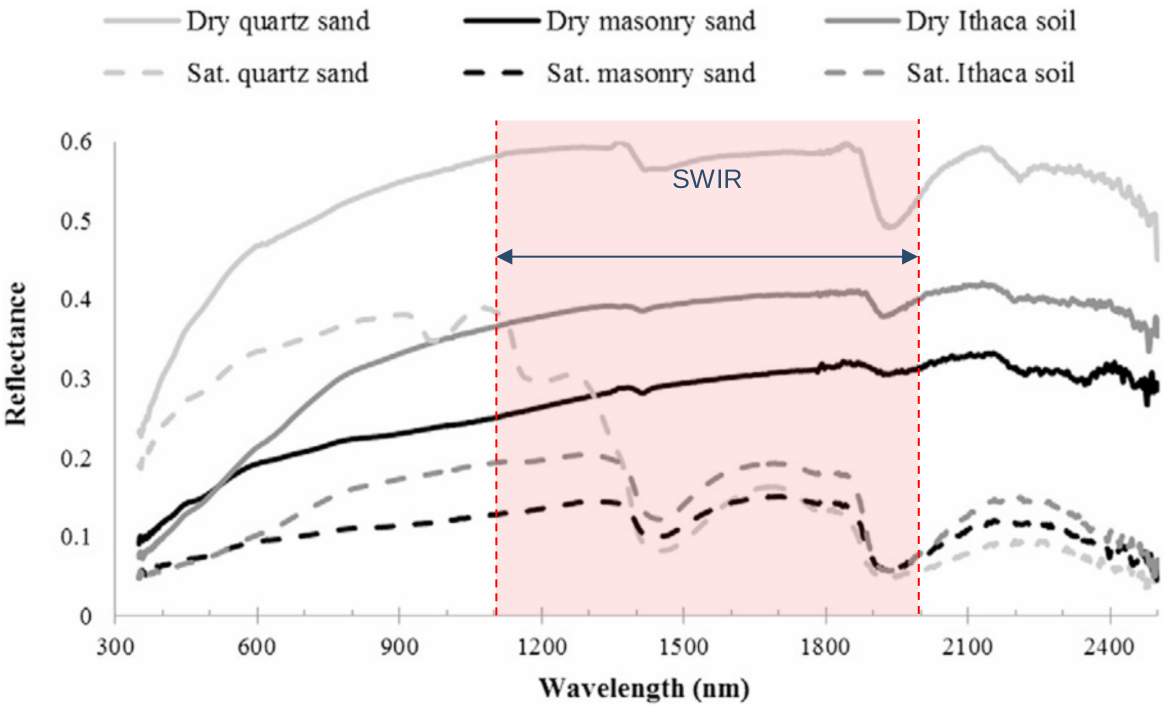
**Table 1.** Methodology and analysis of concrete quality assessment with spectral imaging from research papers.

| Methodology | | | | | | |
|---|---|---|---|---|---|---|
| **Device** | **Wavelength** | **Resolution** | **Samples/Test Objects** | **Pre-Processing** | **Analysis** | **Characteristic Absorption** |
| *The feasibility of short-wave infrared spectrometry in assessing water-to-cement (w/c) ratio and density of hardened concrete* [13] | | | | | | |
| PerkinElmer Lambda 900 UV/VIS/NIR Spectrometer and HySpex SWIR-320m | 1300–2200 nm or 1300–2500 nm | 5nm or not specified | concrete specimen with different w/c ratios | standard normal variate pretreatment and Savitzky–Golay smoothing | partial least square discriminant analysis and relative percentage difference | 1930 nm and 1425 nm |
| *Analysis of concrete reflectance characteristics using spectrometer and VNIR hyperspectral camera* [14] | | | | | | |
| Field portable spectrometer GER-3700 and ASIA Eagle VNIR hyperspectral camera | 350–2500 nm or 400–970 nm | band number: 704 or 1040 | concrete specimen with different w/c ratios and different curing times, concrete structures | normalization | information extraction with ENVI software, processing in Excel | 1950 nm |
| *Identifying the effects of different construction practices on the spectral characteristics of concrete* [15] | | | | | | |
| Fieldspec Pro spectroradiometer | 350–2500 nm | not specified | concrete samples with different treatments (control, no cure, cool cure, heat cure, ...) | normalization by dividing the spectrum with the calibration spectrum (spectralon panel) | analysis of variance, analysis of the increasing of the reflectance in major regions | 450 nm, 1380 nm and 1850 nm |
| *Reflectance spectroscopy as a tool to assess the quality of concrete* in situ [16] | | | | | | |
| "Fieldspec Pro FRQ" VNIR-SWIR spectrometer | 385–2485 nm | 3700 reflectance spectra | cement pastes with different w/c ratios and curing times | normalization | logistic regression, artificial neural network | 465 nm (iron oxides), 1140 nm, 1270 nm, 1450nm (hygroscopic water), * |
| *Assessment of Concrete Degradation with Hyper-spectral Remote Sensing* [11] | | | | | | |
| Spectrometer GER-2600 | 400–2500 nm | 2 nm | concrete samples exposed in carbon dioxide and solution of salt | first and second order derivative of the spectral reflectance | calculation of correlation with degradation depth, multivariant statistical analysis | 440 nm, 1393 nm, 1930 nm, 2127 nm, 2340 nm |
| *Non-destructive chemical analysis of water and chlorine content in cement paste using near-infrared spectroscopy* [12] | | | | | | |
| NIR-Spectrometer (FT-NIR Rocket, ARCoptix, Switzerland) | 900–2600 nm | not specified | cement test pieces with different types of binders containing chloride ions | baseline and bias correction | analysis of peak wavelengths | 1935 nm(water), 2257 nm (Friedel's salt), 1412 nm (Ca(OH)$_2$), 1780 nm (Ettringite) |

Notable historical information observable after hardening

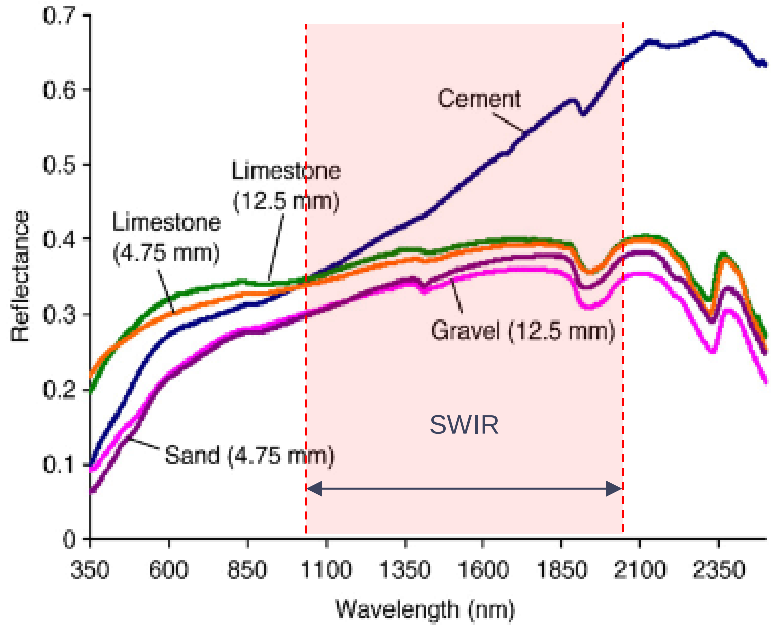
Ptacek et al., 2021
https://doi.org/10.3390/ma14143848

# Early Age Insight from SWIR




Enhanced contrast for moisture levels

Tian et al. http://dx.doi.org/10.1016/j.rse.2015.08.007




Enhanced contrast for cement reflectance

Sridhar et al. https://doi.org/10.1016/j.cemconres.2007.11.012

# Machine Vision vs Computer Vision

# Setting

## ACI Concrete Terminology (ACI CT-23)

**initial setting** — a degree of stiffening of a cementitious mixture less than final set, generally stated as an empirical value indicating the time required for the cementitious mixture to stiffen sufficiently to resist, to an established degree, the penetration of a weighted test device. (See also **final setting**.)

**final setting** — a degree of stiffening of a cementitious mixture greater than initial setting, generally stated as an empirical value indicating the time required for the cementitious mixture to stiffen sufficiently to resist, to an established degree, the penetration of a weighted test device. (See also **initial setting**.)

**set time** — the lapsed time from the addition of mixing water to a cementitious mixture until the mixture reaches a specified degree of rigidity as measured by a specific procedure.

'empirical value' indicating sufficient stiffness to resist penetration as measured by a specific procedure

### Designation: C403/C403M – 23

**Standard Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance**[1]

Sieve out +#4 material (4.75mm)
Initial set: Penetration resistance = 500 psi
Final set: Penetration resistance = 4000 psi
Biggest and smallest needle: 29mm Ø – 4.5mm Ø
**First test recommended at: 3 to 4 hours!**

### Designation: C807 – 21

**Standard Test Method for Time of Setting of Hydraulic Cement Mortar by Modified Vicat Needle**[1]

Time of set: Penetration resistance = 300g 10mm
Needle size: 2.0mm Ø
**First test recommended at: 30 min**

Equipment images from https://myerstest.com/

# Effect of temperature

+25°F

~Half initial set time

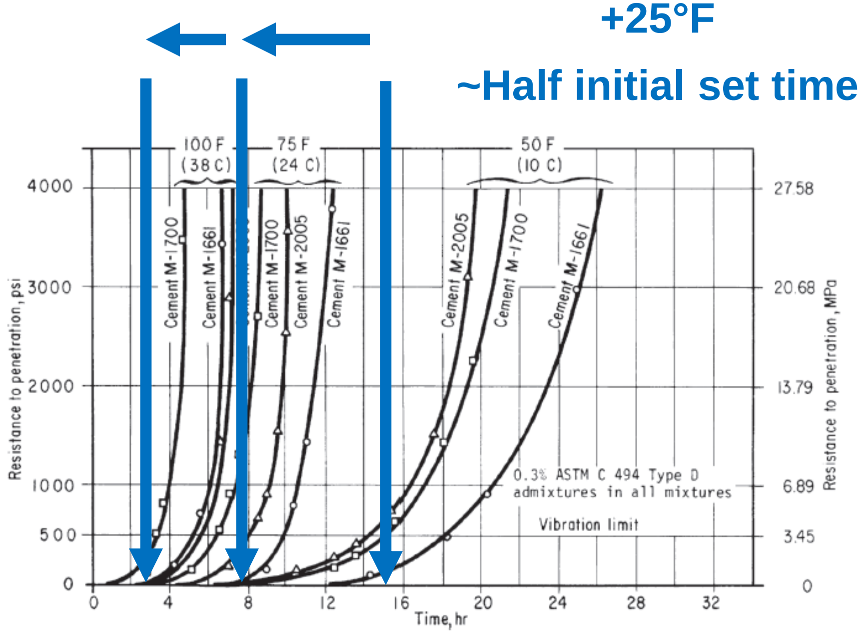



*Fig 4.6—Effect of temperature and brand of cement on setting time characteristics of concrete mortars (Tuthill and Cordon 1955).*

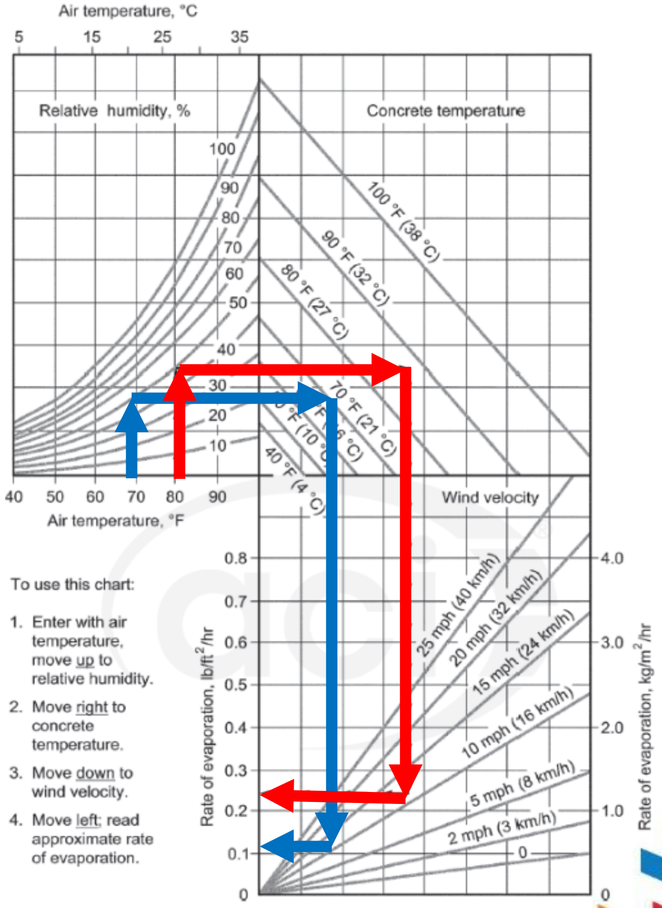



*Figure 4.1.4*

*Figures from ACI PRC-305-20: Guide to Hot Weather Concreting*

# Setting at early times

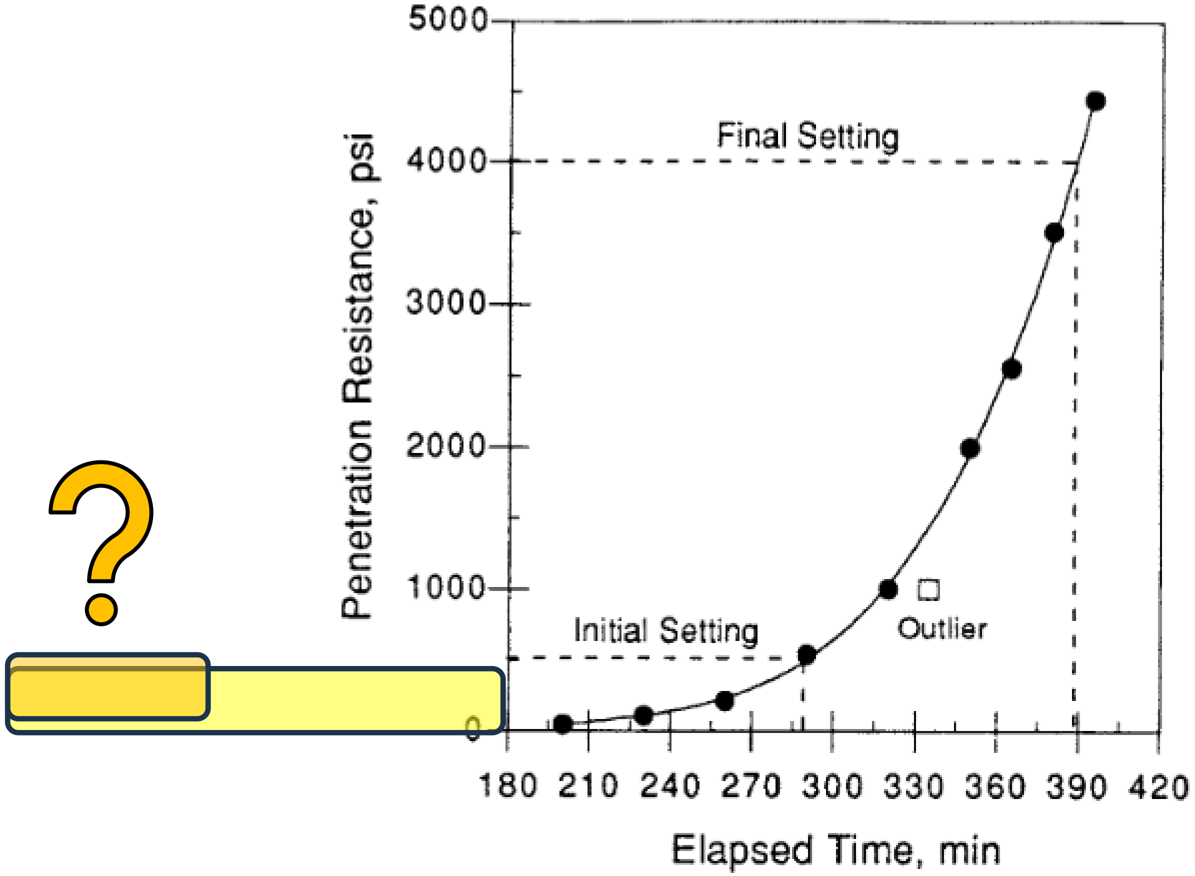
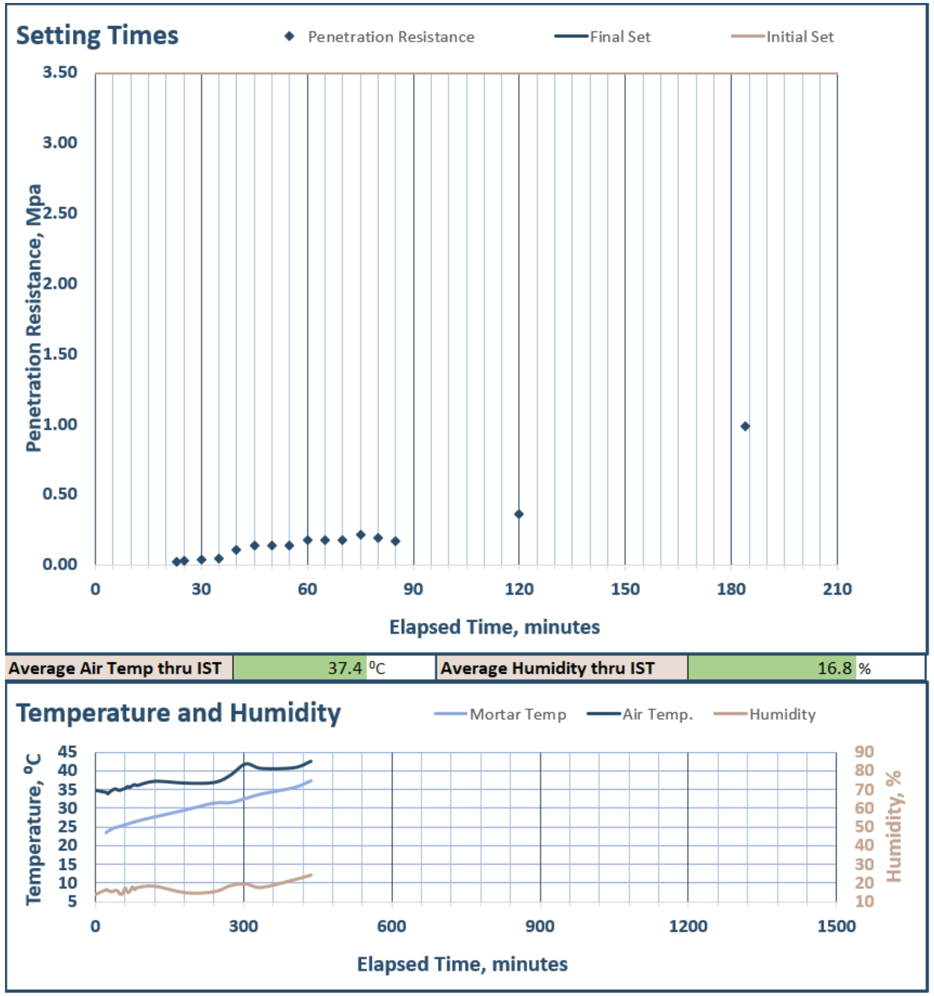



*Figure excerpt from ASTM C403*

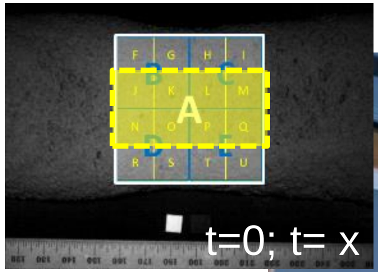
# Setting at early times

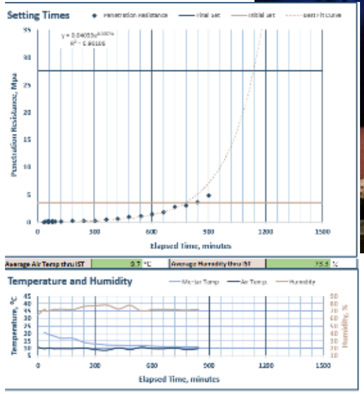
Small increments of force required to penetrate 1 inch



# Setting Experiments

- Focused on a commercially available 3DCP mortar mix with an ICC-ES report for design values.
- Manipulate setting behavior by testing at 3 target temperatures: 10°C (50°F), 24°C (75°F), 38°C (100°F)
- Extrude a construction scale bead (~50mm wide x ~20mm thick) for image data collection and cast C403 test specimen.
- Capture early penetration resistance data (~15-120 minutes) at 5-minute increments.
- Capture multispectral image data at bands of interest at 5-minute increments.

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SBIR
America's Seed Fund

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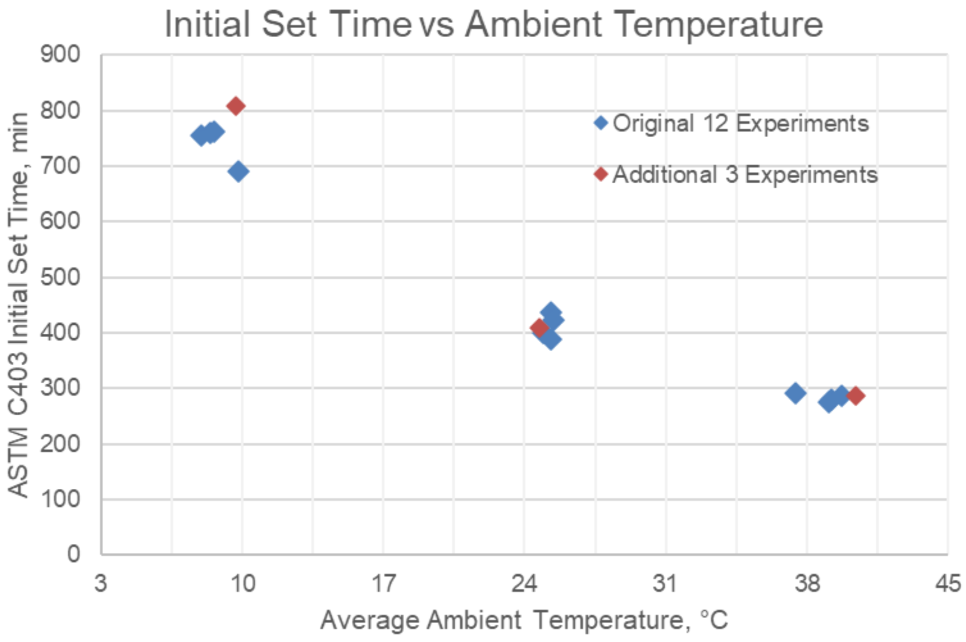
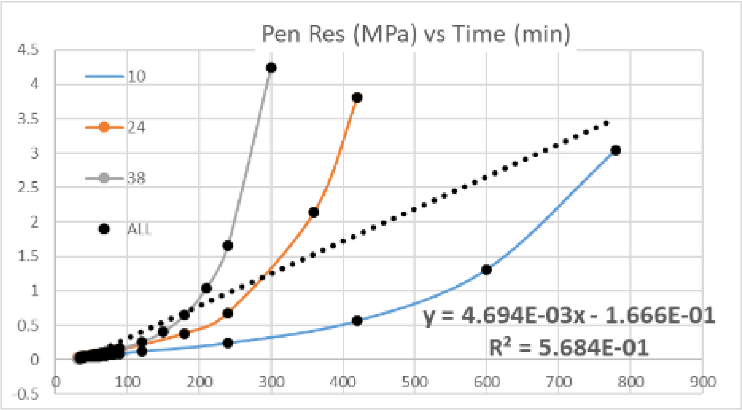
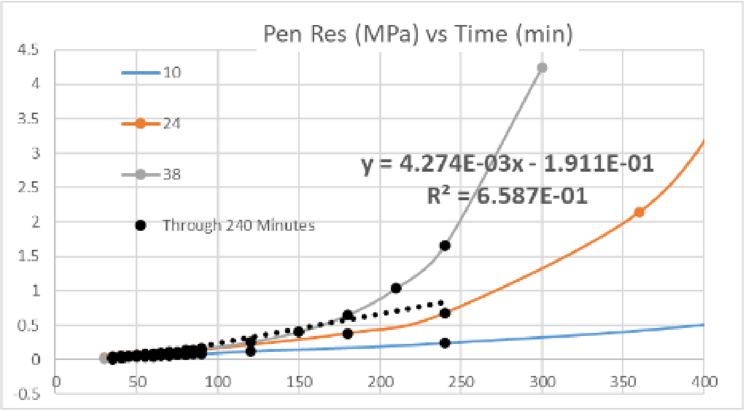
# Setting Results

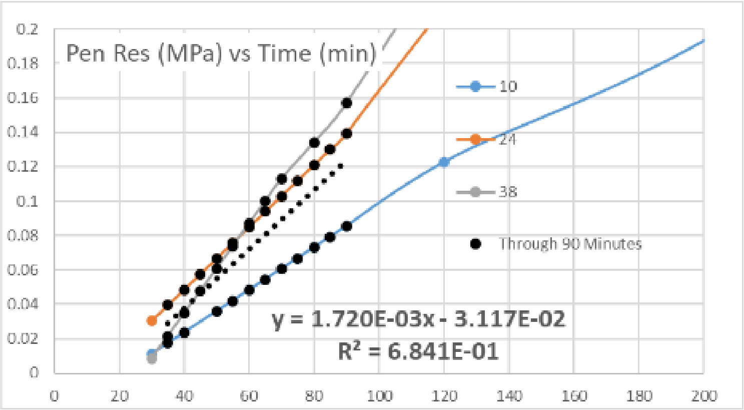
| ASTM C403 Setting Time Summary | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Target Temp. | Number of Tests | Initial Set Time | StdDev | Final Set Time | StdDev | Air Temp. to IST | StdDev | Humidity to IST | StdDev |
| **10** | 4 | **769** | 27 | **1213** | 74 | **8.7** | 0.8 | **58.7** | 17.2 |
| **24** | 4 | **414** | 20 | **603** | 18 | **25.2** | 0.2 | **36.3** | 12.2 |
| **38** | 4 | **285** | 6 | **421** | 13 | **38.9** | 1.0 | **16.0** | 3.3 |

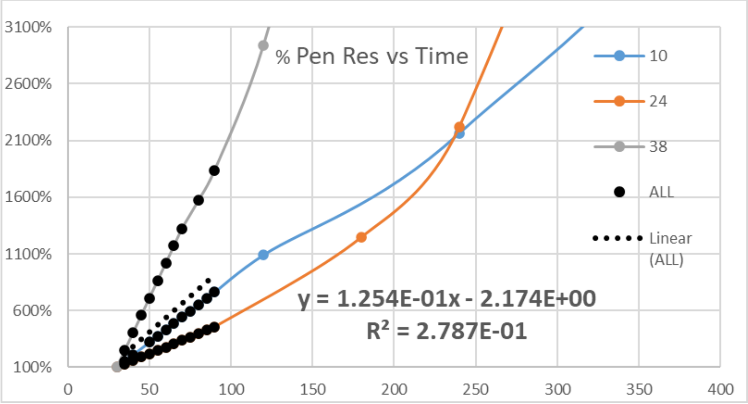


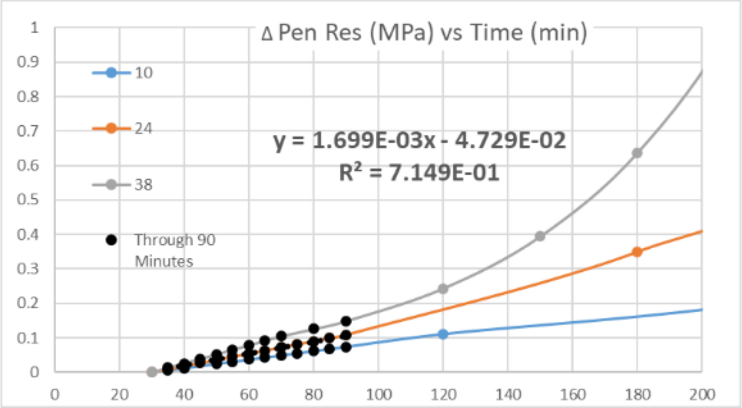

# Correlations to Penetration Resistance – vs Time



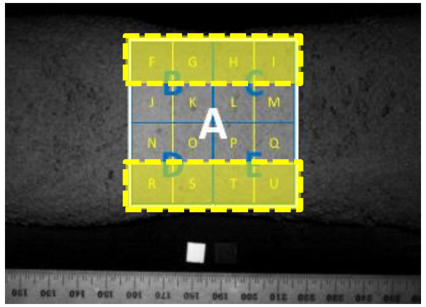



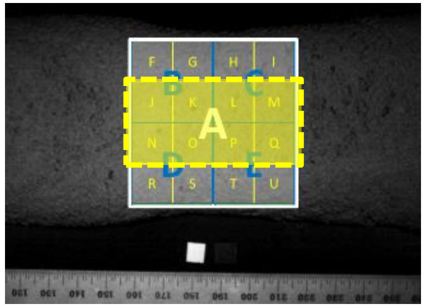



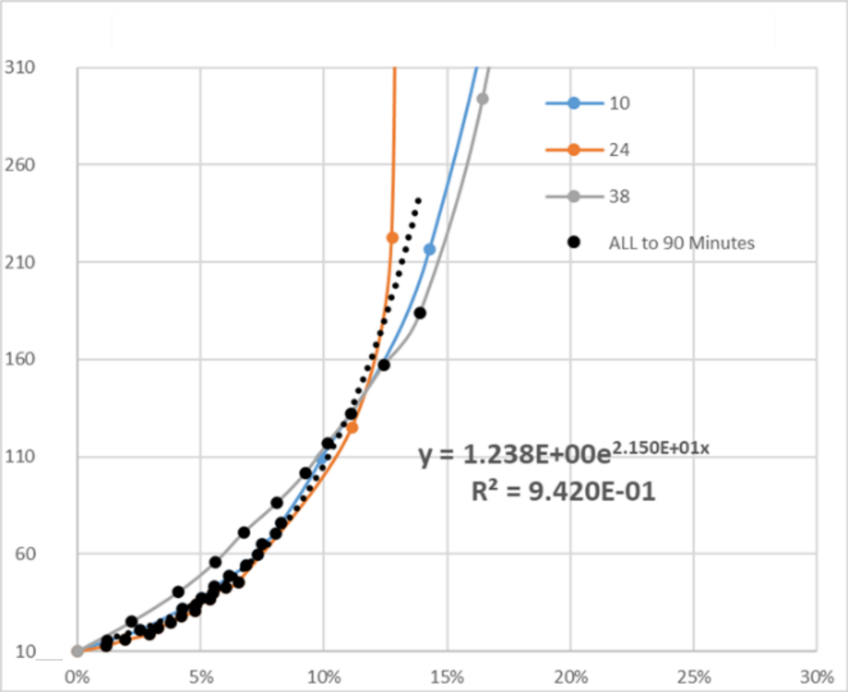

Highest $R^2$:

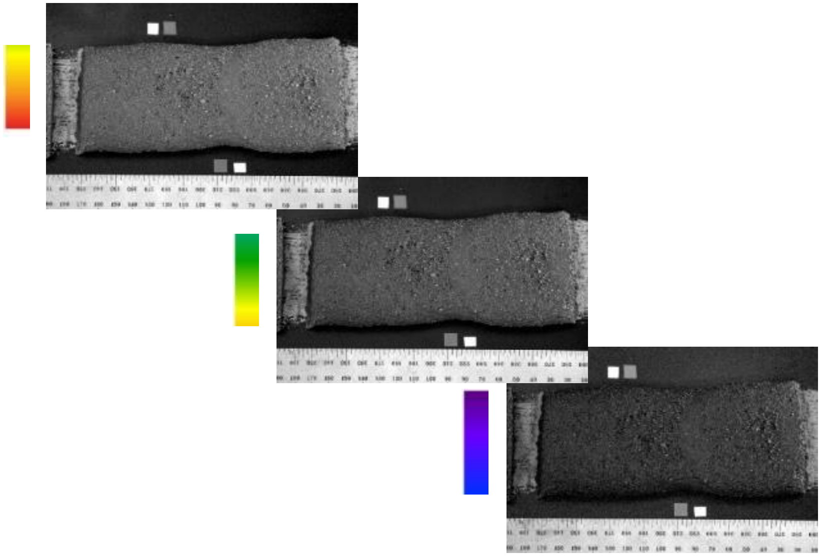
Time: 71.5%

# Correlations to Penetration Resistance – vs Imagery



Highest $R^2$:

Time: 71.5%

SWIR: 94.2.%

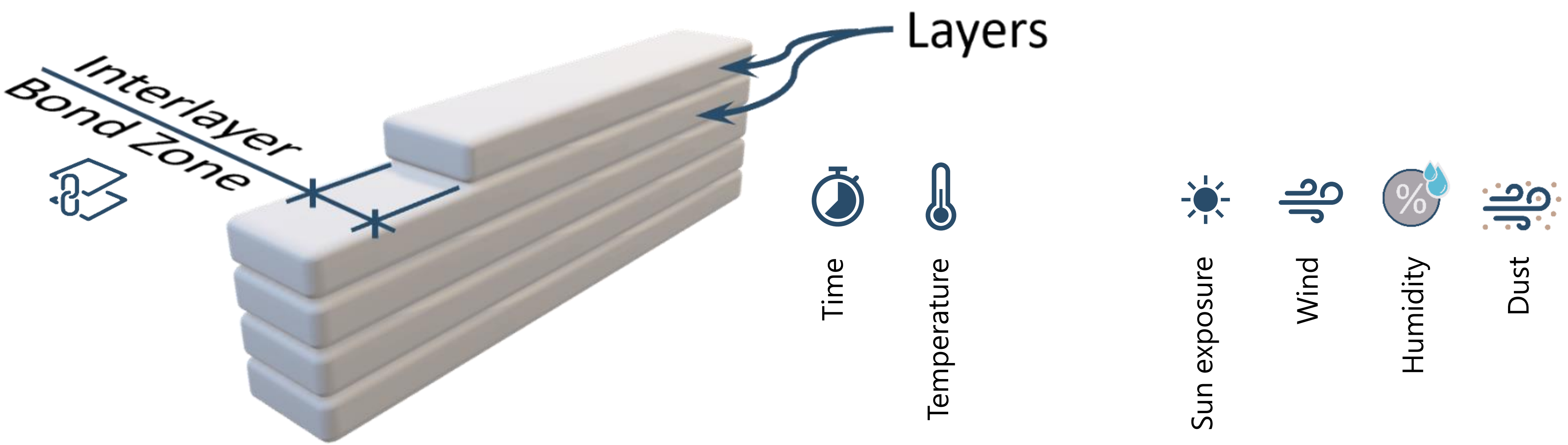
RGB: ~66%

# Setting and Bonding

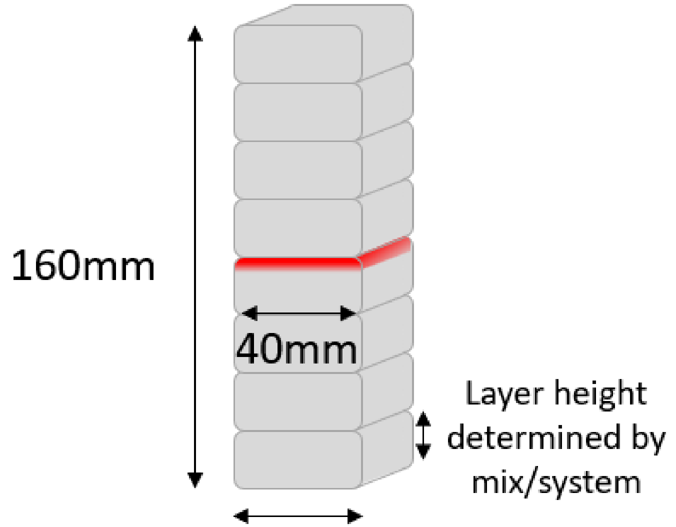
- Cold joint formation is affected by progress towards setting.
- More likely to occur in hot weather conditions.
- Found to occur prior to initial set time (as measured by C403).
- Found to occur above a penetration resistance threshold independent of ambient temperature.

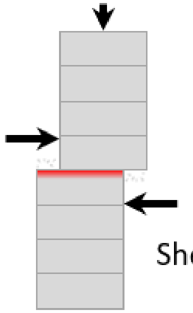
Illangakoon et al. https://doi.org/10.1016/j.conbuildmat.2019.03.093

# Interlayer Bonding in 3DCP

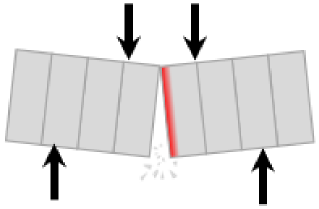


# Bonding Experiment Plan



Shear bond testing in wall plane

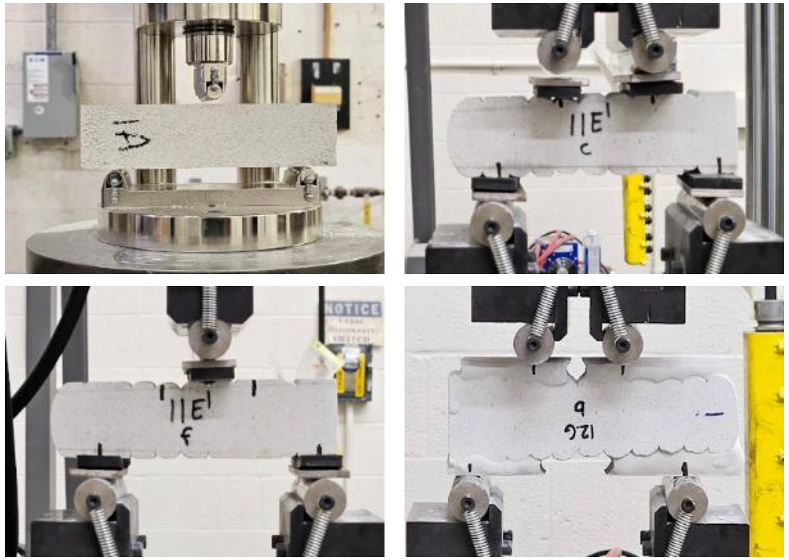


Flexural bond testing out of wall plane

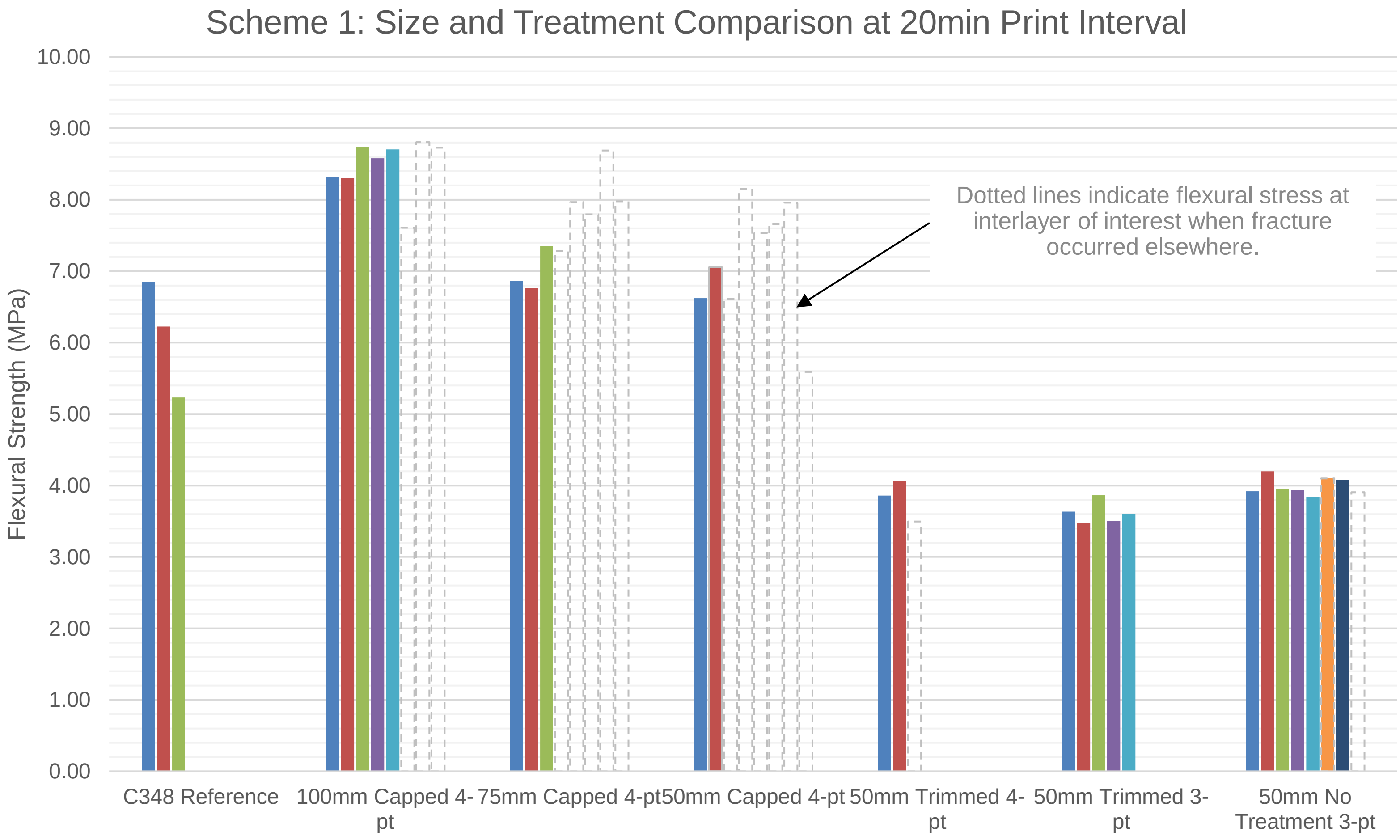
| | test method/ specimen treatment | | bond strength varied with time | | bond strength varied w/ time & temp | |
|---|---|---|---|---|---|---|
| | Scheme 1 | | Scheme 2 | | Scheme 3 | |
| Wall | Print Int. | Temp | Print Int. | Temp | Print Int. | Temp |
| A | ~20 min | ~24C | 10 min | ~24C | 10 min | ~38C |
| B | ~20 min | ~24C | 20 min | ~24C | 50 min | ~38C |
| C | ~20 min | ~24C | 30 min | ~24C | 90 min | ~38C |
| D | ~20 min | ~24C | 40 min | ~24C | 10 min | ~24C |
| E | ~20 min | ~24C | 50 min | ~24C | 50 min | ~24C |
| F | ~20 min | ~24C | 60 min | ~24C | 90 min | ~24C |
| G | ~20 min | ~24C | 70 min | ~24C | 10 min | ~10C |
| H | ~20 min | ~24C | 80 min | ~24C | 50 min | ~10C |
| I | ~20 min | ~24C | 90 min | ~24C | 90 min | ~10C |

x5 cycles or 'regimens'

# Bonding Experiment Execution – Regimen 1 w/o imaging



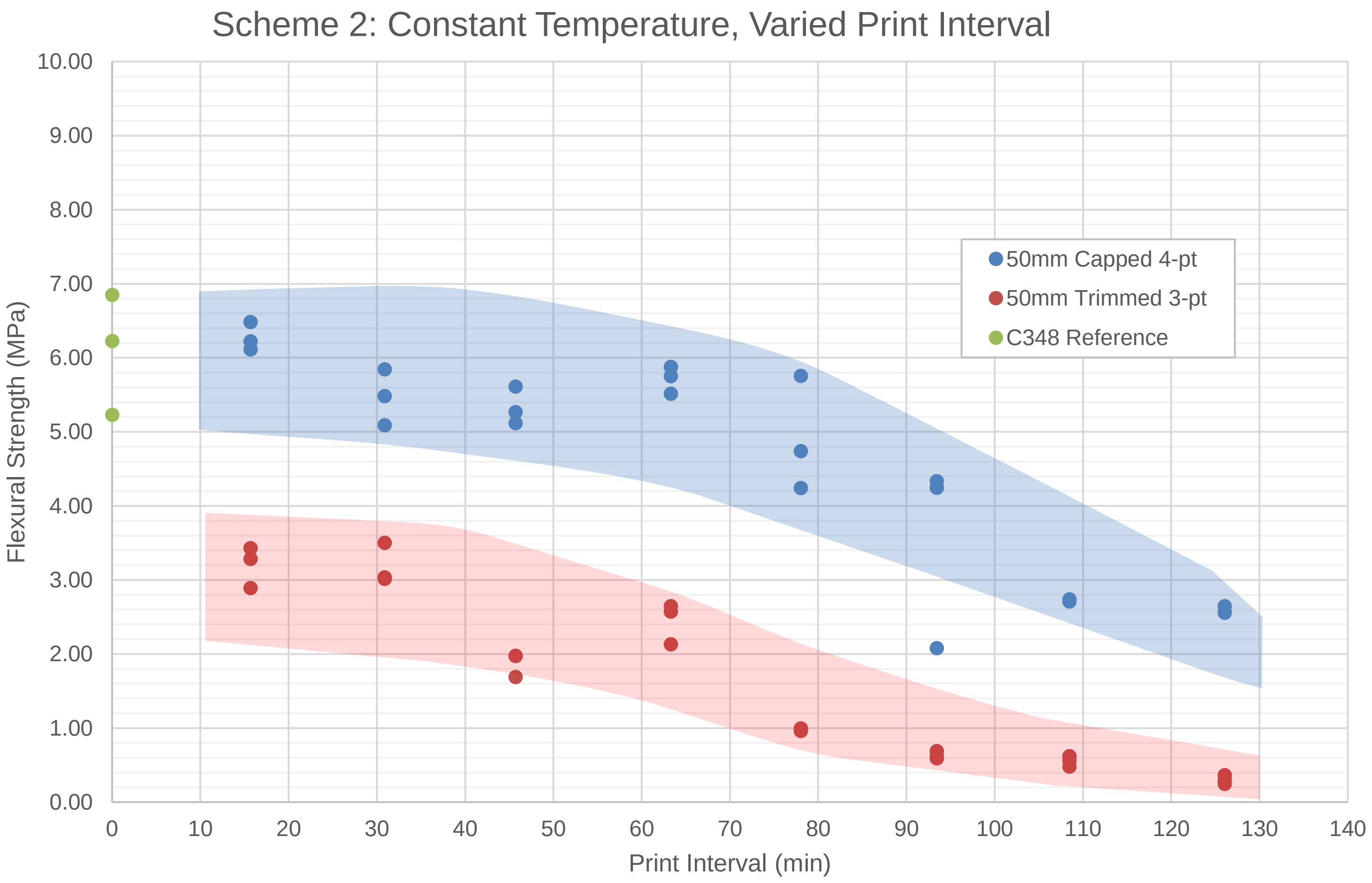
# Bonding Results – Regimen 1




**Takeaways:**

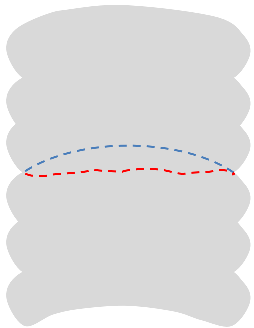
- The capping method employed appears to have erroneously boosted flexural strength.
- The 4-pt and 3-pt method appeared to yield similar results (very little data to hang our hat on here).
- The repeatability of all specimen varieties rivaled or exceeded the repeatability of the C348 test.
- High variation in layer widths along height of specimen can create higher stress zones at unintended interlayers (and makes it harder to properly situate in the test jig).

# Bonding Results – Regimen 2




**Takeaways:**

- Capping method results are higher than trimmed method results. But also note 4-pt vs 3-pt.
- General but erratic reduction in flexural strength as print interval is increased.
- Relatively repeatable results with some exceptions. Again rivaling or better than C348 results.
- Possible anomalous performance of ~60min interval test wall.
- Variation in layer widths along height of specimen negatively affect ability to properly place specimen for load testing.



# Bonding Experiment Execution – Regimen 2 w/ imaging

Ready to print at NIST AC Lab.

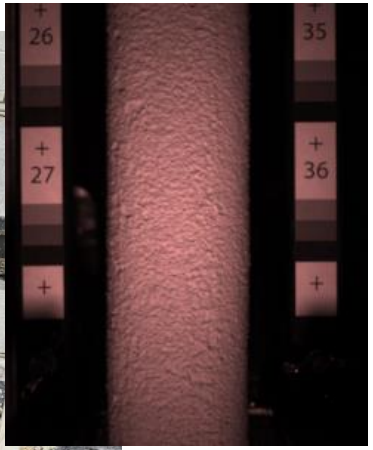
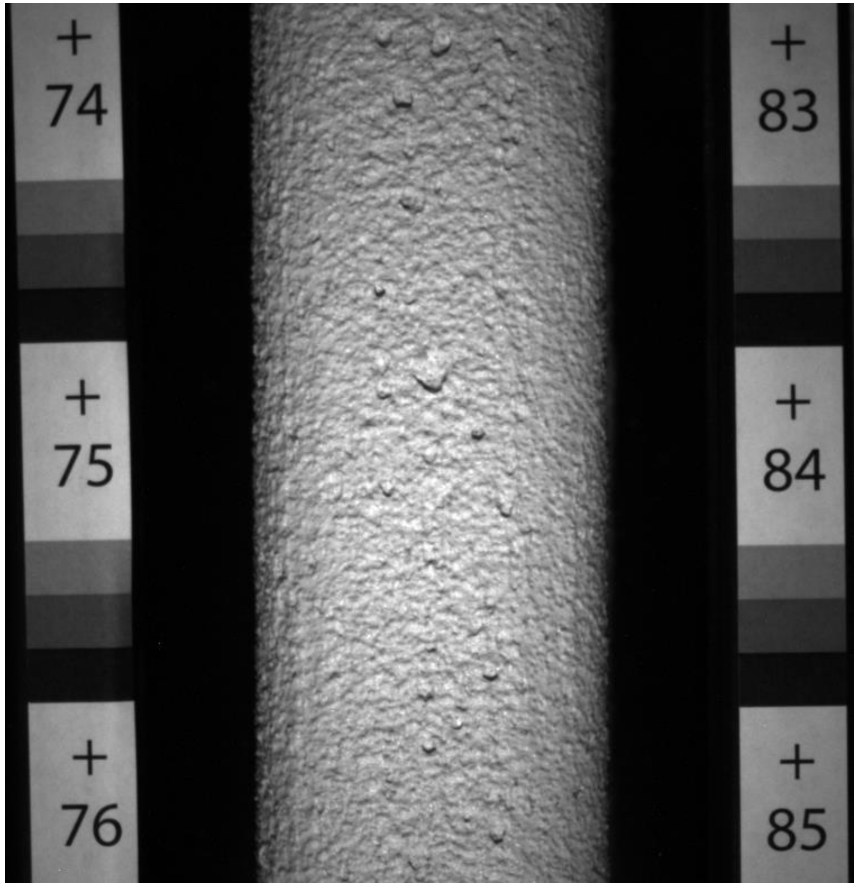



Image data taken on interlayer of interest just after printing and just before placement of next layer.

# Future Work

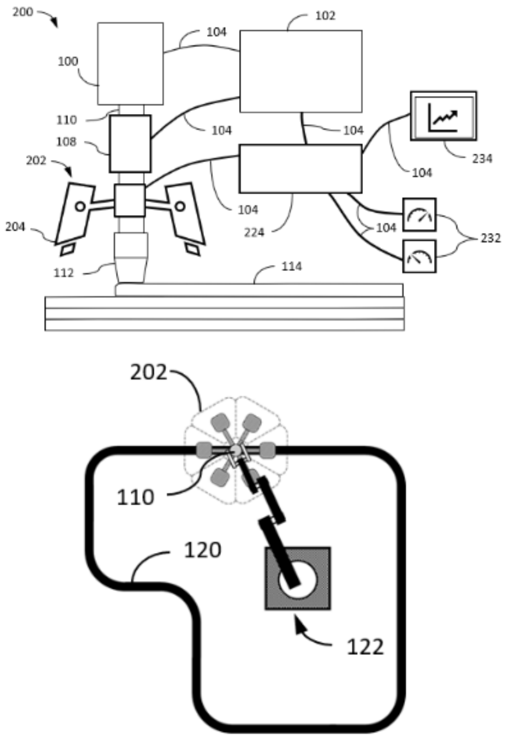
VISION SETTING BONDING **FUTURE**

# Imaging Correlation to Interlayer Bond Strengths

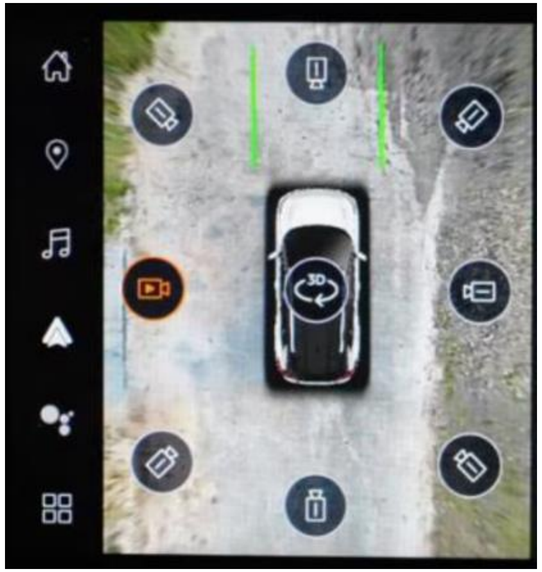



- ~1800 training data points after completion of next 3 print experiment cycles
- Manual feature extraction and correlation
  → machine learning approach
  → supervised deep learning approach
- Move to more sophisticated procedure of measuring setting progress, capturing force-displacement curves of C807 Vicat needle penetration rather than single force or time values.
- Begin introduction of wind, humidity, and dust effects on image parameters.

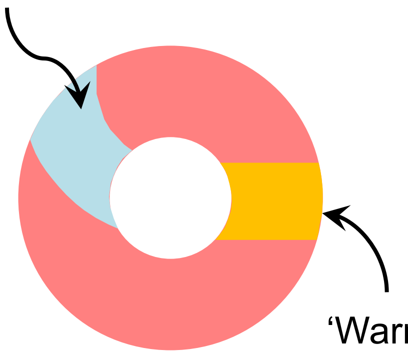
# Nozzle-mounted Field Prototype Pilots



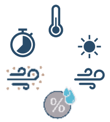

*ARtx PCT Patent Pending*

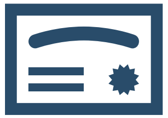


Birds eye vehicle image excerpt from: https://www.autotrader.com/car-shopping/360-camera-car

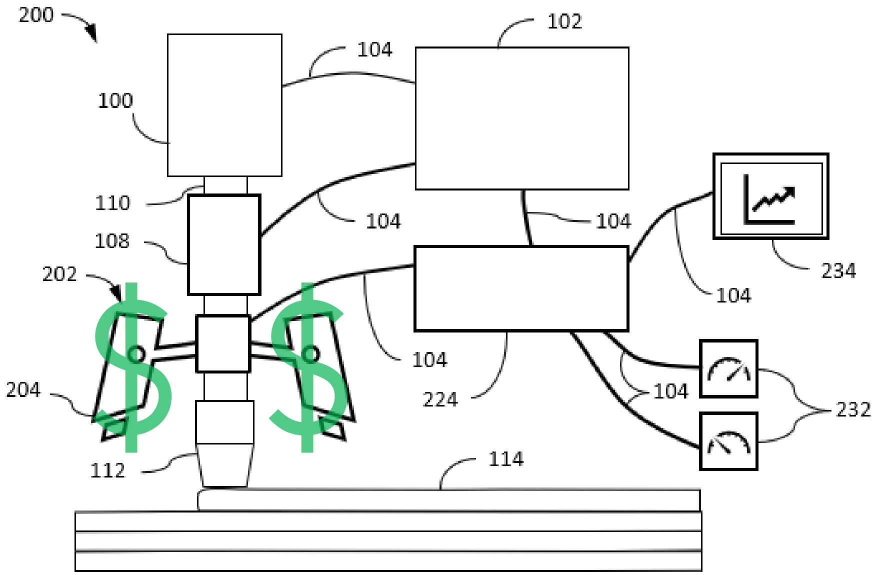



- Bead quality
- Bead history during interlayer time
- Setting progress
- Bond strength





# Cost Horizon

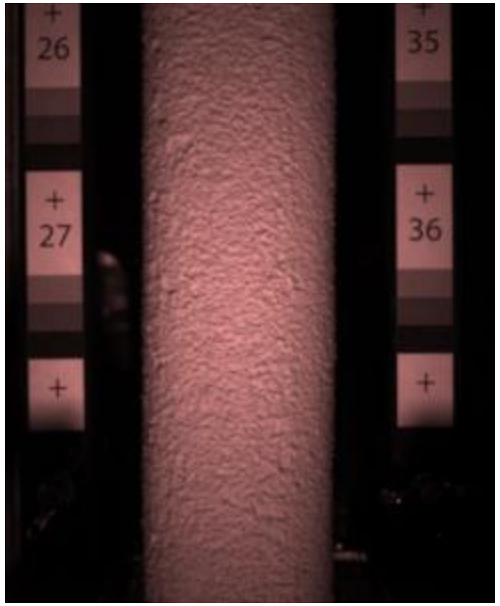



- Primary driver of cost of system is the camera technology.
- Colloidal quantum dot (CQD) camera technology presents an opportunity to dramatically reduce costs.
- Production volume component cost is expected to fall below $10,000 within two years.

# Final Takeaways

1. Cameras can image reflected light in a spectrum ~7 times what the human eye can see, in precise wavelength ranges designed to observe particular phenomena.
2. Machine vision and computer vision can employ learning models that incorporate physics-based image parameters along with machine-generated parameters.
3. Standards for measuring setting time do not generate quality data for 3DCP mortar mixes, particular 2K mixes. New standards are needed.
4. Standards for measuring bond strength for printed  3DCP mixes are under development but currently exist as modifications to ASTMs not originally intended for additive construction.
5. Research has demonstrated that computer vision can predict setting progress reasonably well  without knowledge of time or temperature history based on a current image and an image immediately after bead extrusion.
6. Research is currently underway to further tie these image correlations to interlayer bond strength with the goal of creating a nozzle-mounted quality control system.

# Questions

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