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Development of Hybrid Control Charts for Active Control and Monitoring of Concrete Strength

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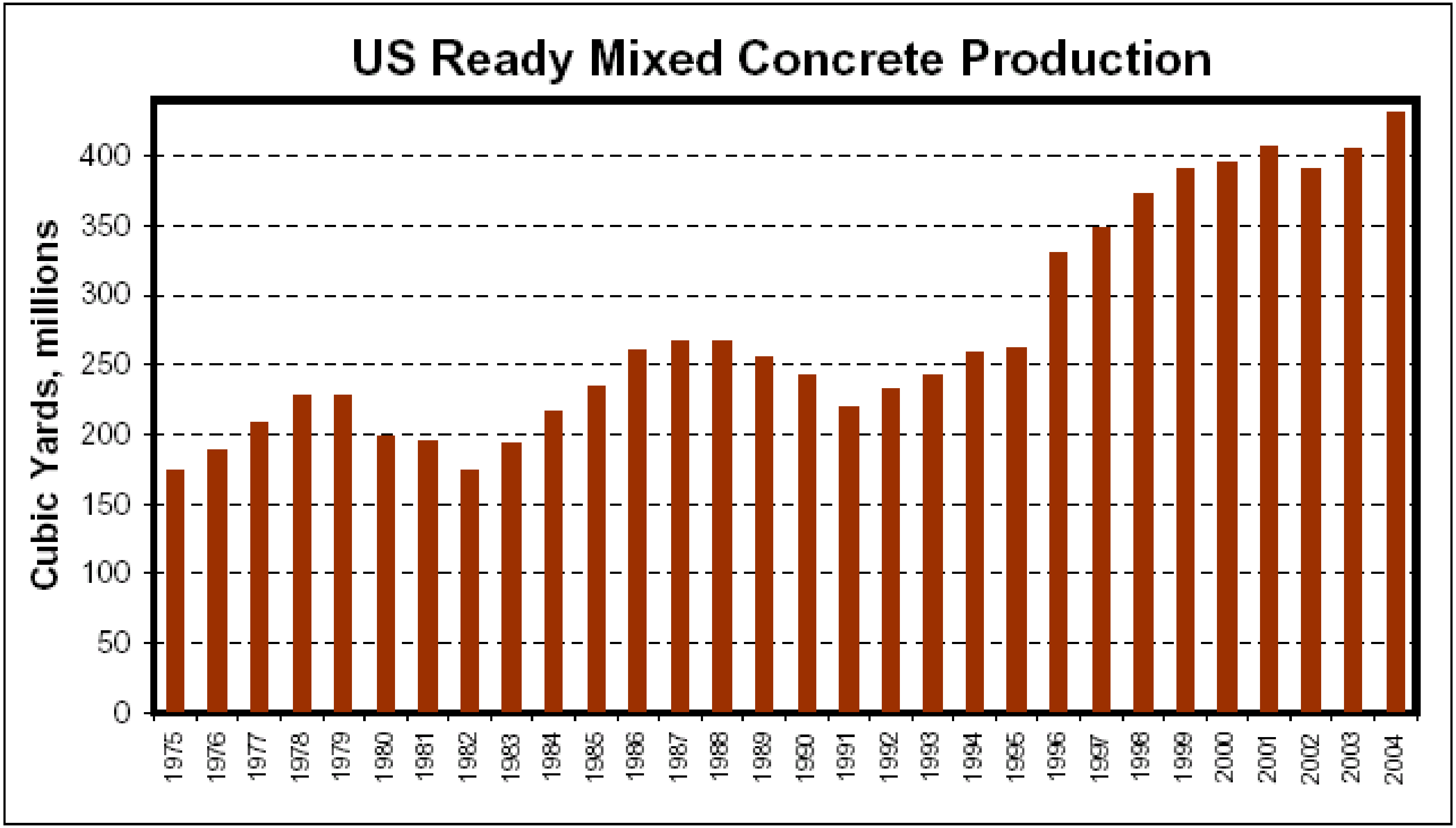
Outline

- Overview of the Sustainability and Economical Aspects
- Specifications vs. QC vs. pay factors in concrete specifications
  - Disjointed correlations
  - Risk level involved unknown
  - Testing of materials, and acceptance vs. penalty criteria
  - Statistical data analysis
  - Process Control integration
- New Challenges and opportunities
  - Multiple parameter objectives
  - Conflict resolution, Waste minimization, cost containment

Motivation for Sustainability based design

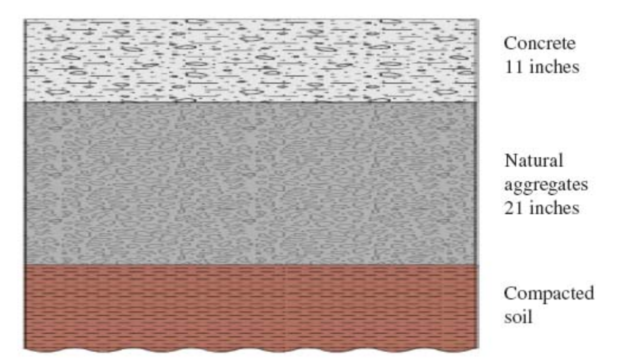
- Address the economics and alternative solutions for quality Concrete specifications
- Innovative approaches to design, evaluate, and control concrete properties
  - Implementation of Statistical Process Control in Construction industry
  - Rational evaluation of Mechanical properties, ductility, and durability, a multivariate analysis
  - Economy
  - Risk aversion

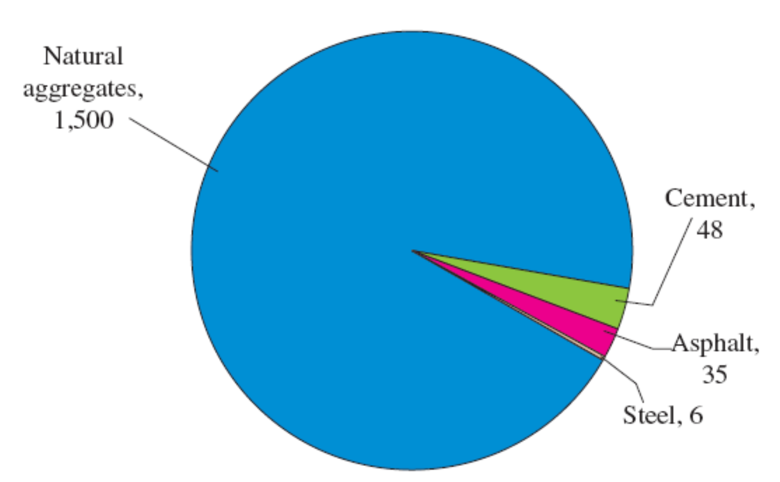
Sustainability: Concrete Consumption in US



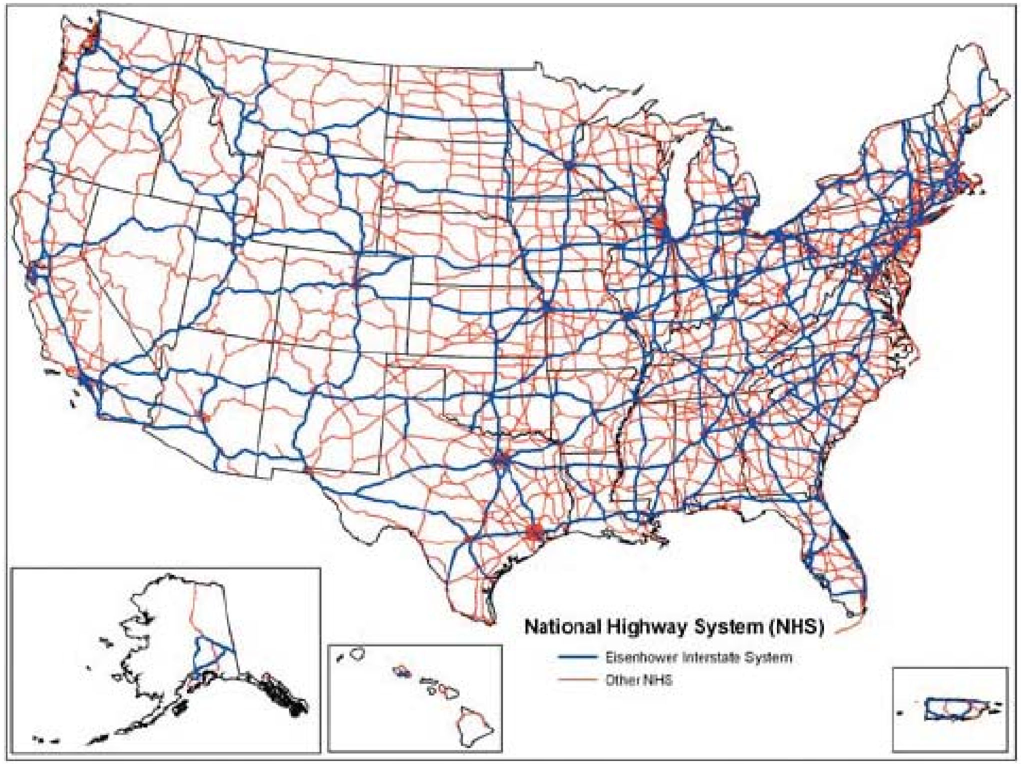
Materials use in the Interstate Highway System

- If a generic US inter-state highways were to be built in a single year, it would utilize more than:
  - 48 Mt of cement, and (40% in 2005)
  - 35 million metric tons (Mt) of asphalt, (100% of 2005)
  - 1.5 billion metric tons (Gt) of aggregates, (>50% in 2005)
  - 6 Mt of steel





million metric tons



Van Oss, 2006

Demand for Concrete Materials in Arizona

At $100-$400 per cubic yard, it translates to $1.5-6 Billion industry in Arizona

2004 U.S. Ready Mixed Concrete Production

State	Cubic Yards	% of Total	Change from 200[illegible]
Alabama	6,038,000	1.4%	2.8%
Alaska	642,000	0.1%	6.0%
Arizona	15,130,000	3.5%	14.1%
Arkansas	4,309,000	1.0%	7.2%
California	52,255,000	12.1%	7.3%
Colorado	8,960,000	2.1%	6.5%
Connecticut	3,019,000	0.7%	8.5%
Delaware	662,000	0.2%	3.9%
Dist. of Columbia	698,000	0.2%	-2.6%
Florida	35,634,000	8.3%	12.9%

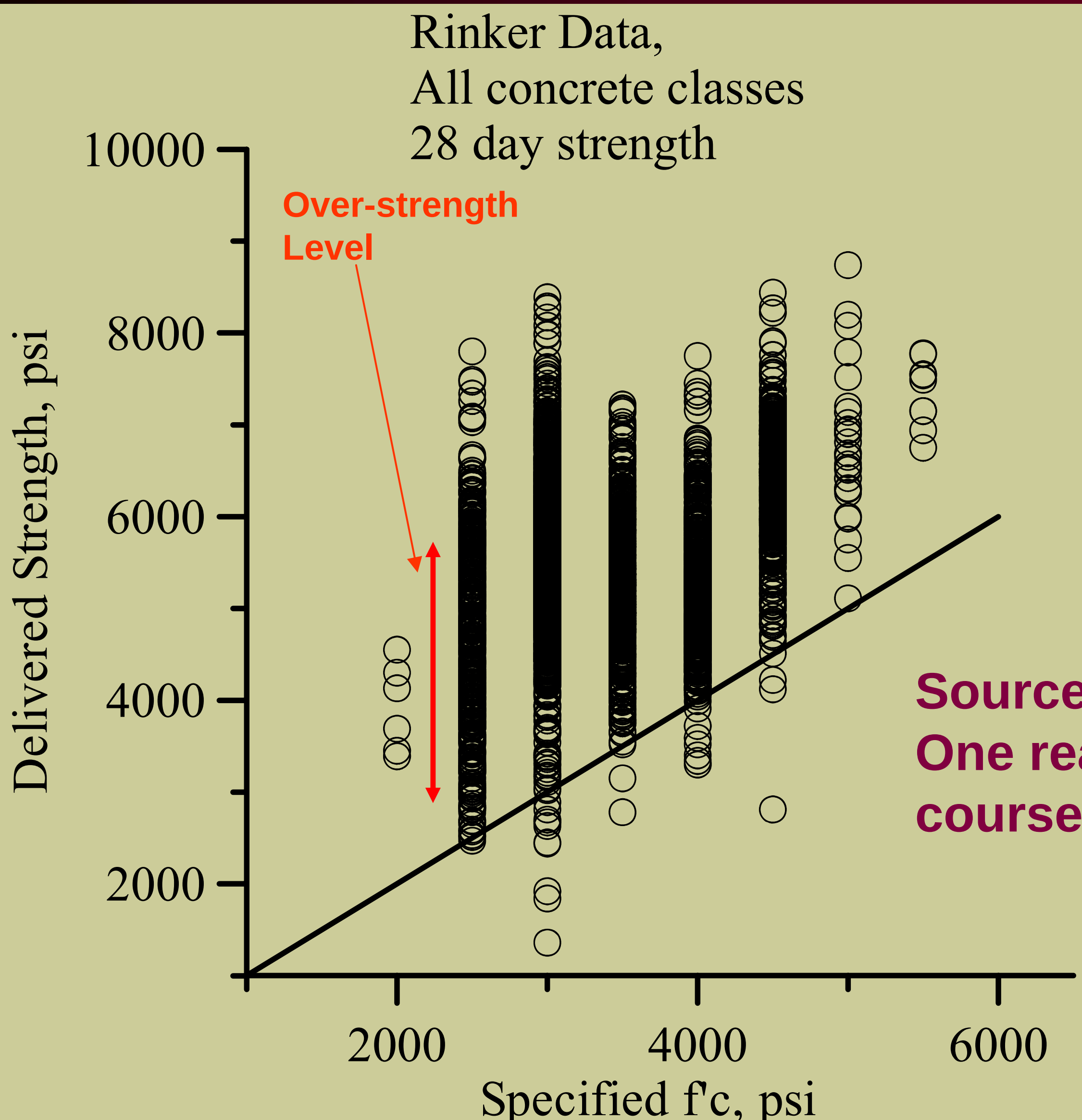
Giga Volume of Materials

- Arizona's demand is on average at 15 million cubic yards of concrete.
- About 7.8 million lbs of cement and other mineral admixtures.
- Increasing flyash use from 20% to 30% cement replacement, will save about 22 million dollars (from 55 to 77 million dollars) statewide.
- If we could save 1 sack of cement per cubic yard used, then the savings would amount to 100 million dollars per year.

Problem Description

- Objective
  - Reduce Construction Costs through use of economical materials
  - Controlled risk through rational acceptance criteria.
- Strategy:
  - increase competitiveness among project bidders
  - Develop quality materials and specifications.
  - New procedures for mix design, specifications.
  - Better pay factors for contract administration.
- Hypothesis
  - Performance enhancing admixtures, supplementary cementitious materials, in addition to *Statistical Quality Control Procedures can be used* to develop a set of guidelines for *Quality Materials and specifications*.

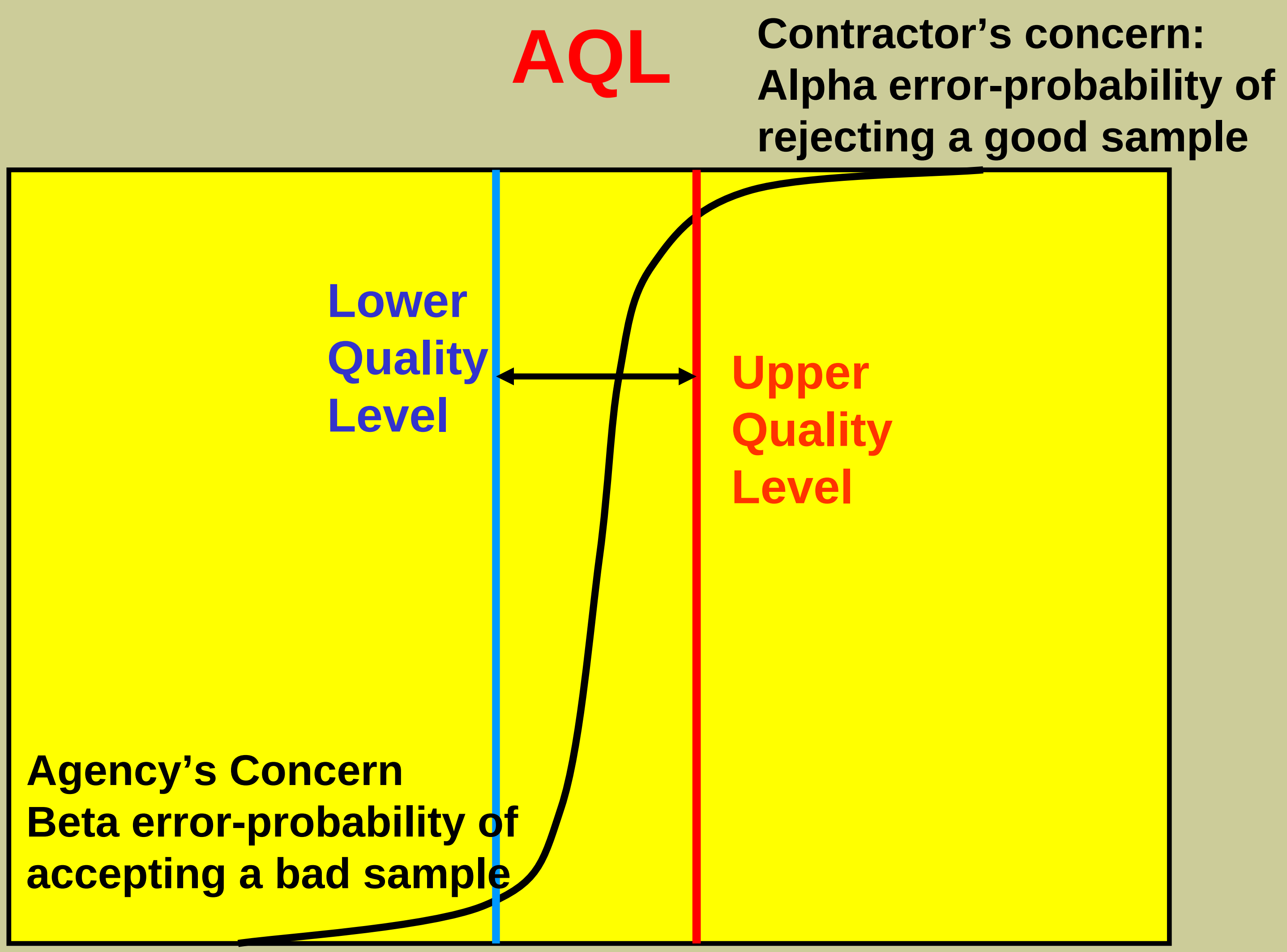
Concrete Specified vs. Delivered



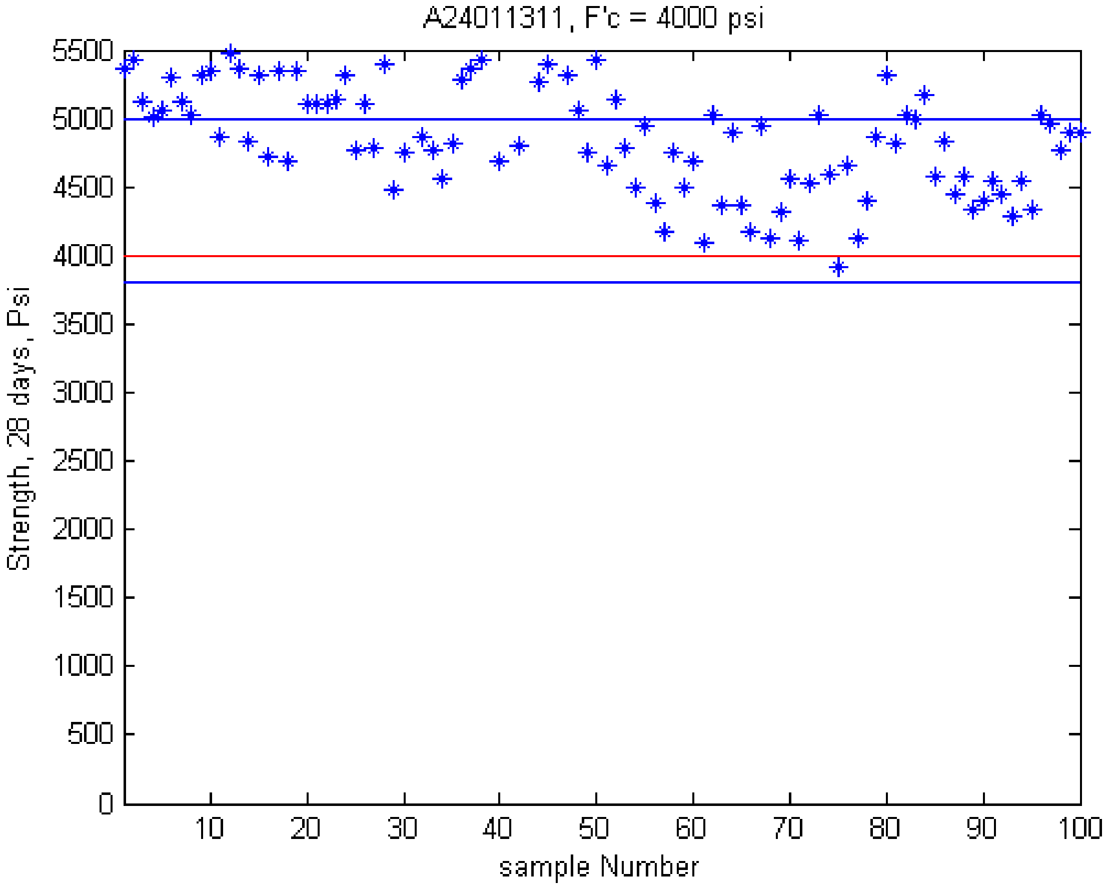
Each data point = 100 cubic yards

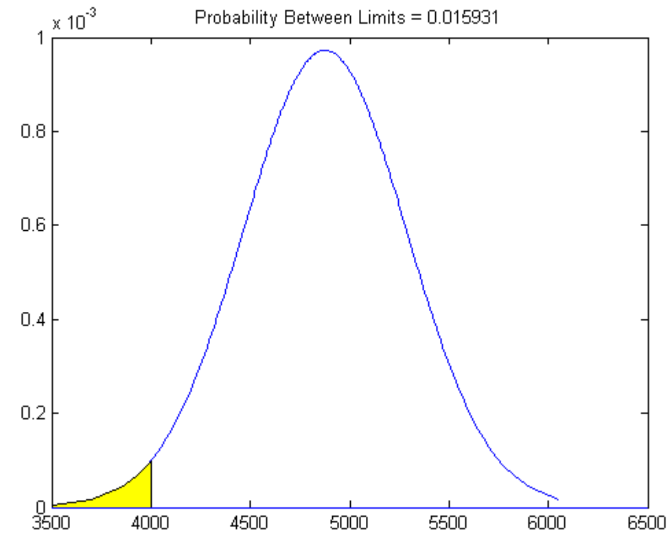
Source: ADOT Fast Database for One ready mix supplier over a course of two years

Risks and rewards

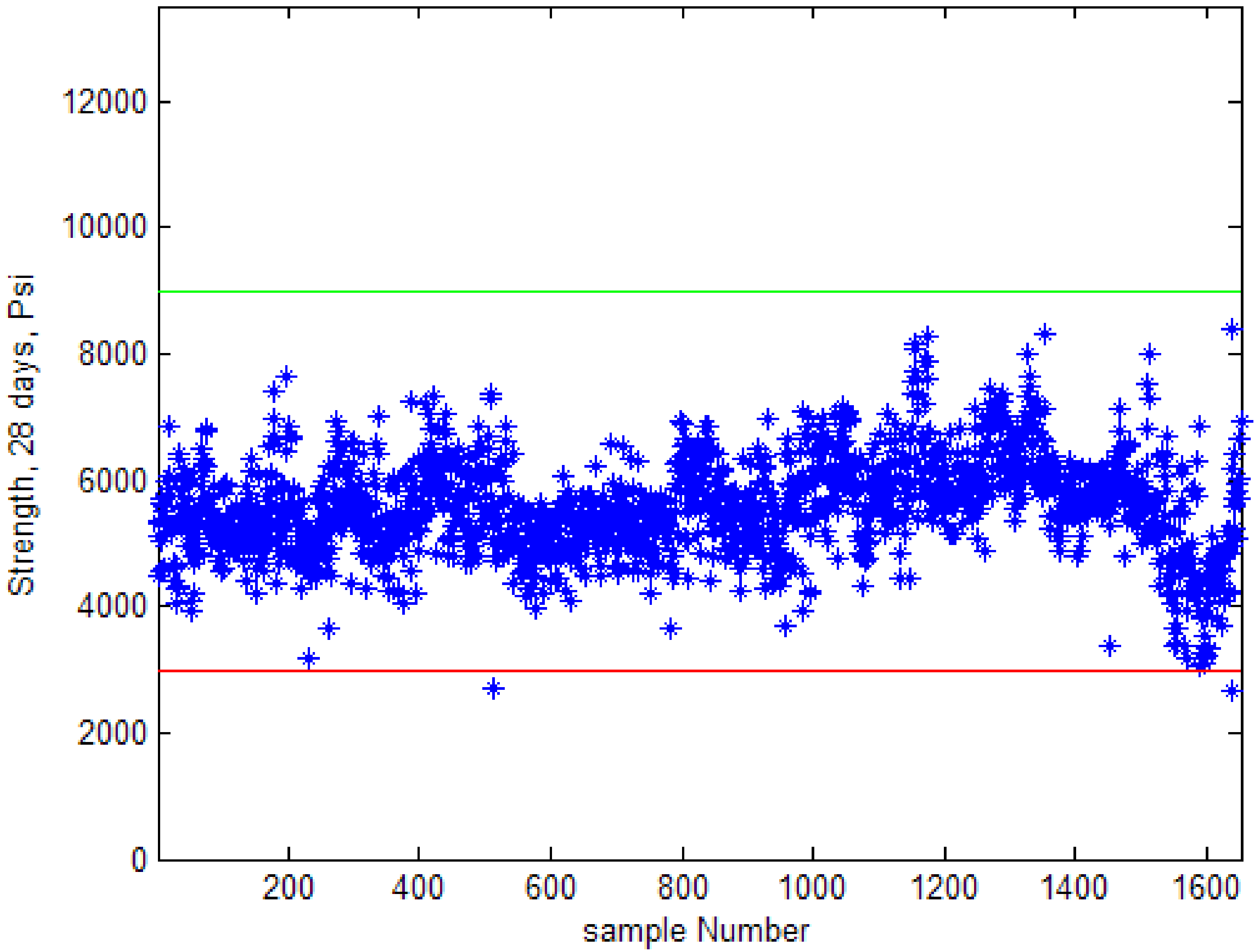


Where are we today?





Test Case- 3000 psi concrete



Sustainability in the cement industry

- Quality control and monitoring can play a significant role in the cement industry's goal*.
  - Improve the energy efficiency
  - Improve product formulation to reduce manufacturing energy consumption and minimize the use of natural resources

- Natural variability in the production, delivery, and construction systems must be well understood before efforts and regulations for sustainability will be continuously effective.
  - Statistical Process Control (SPC) helps to identify natural (common) variability and assignable cause variability

*** Portland Cement Association's 2009 Report on Sustainable Manufacturing**

Application of Statistical Process Control to strength data

- A cumulative sum (CUSUM) control chart for individual observations is applied to monitor concrete strength (Cement and Concrete Institute, CCI, 2001) & (Day, 2006)
  - Three types of CUSUM chart for monitoring
    - The mean strength
    - The Mean range strength
    - The correlation between predicted and actual strengths.
  - The Average strength should be separately calculated for each project since different jobs and suppliers will affect the average strength calculation (ACI 214, 2002).
- Standard deviation and coefficient of variation approach (Sykora, 1995) is useful for comparing variation within a plant, not from plant to plant
- A combination of two or more methods can improve the reliability and accuracy (Leshchinsky, 1991)

Application of Statistical Process Control to strength data

- Combine two control charts to detect the process variations as soon as possible
  - A standard run chart
    - Presents the stability of the process variation over time
  - CUSUM (Page, 1954) or Exponentially Weighted Moving Average (EWMA) control chart (Roberts, 1959).
    - Efficient in detecting small process shifts (1.5σ or less) (Montgomery, 2008)
    - The difference is the weight functions applied to current and past data values.

      CUSUM: constant weight factor

      EWMA: an exponential weight factor
- Control charts are based on an assumption of normality

Cumulative Sum (CUSUM) chart, Page (1954)

– Sum of the deviations of the sample measurement (such as an individual observation or average of several observations) from a target (product specification).

$$C_i = \sum_{j=1}^{n} \left(x_j - \mu_0 \right)$$

where C_i is the sum of the deviations from target for all observations up to and including the *i*th observation

x_j is the *i*th observation

μ_0 is the target value

n = number of observations

– A deviation above target is called a one-sided upper cusum (C^+)

– A deviation below the target is called a one-sided lower cusum (C^-).

Cumulative Sum (CUSUM) chart

- One-sided CUSUM chart

$$C_i^+ = max[0, x_i - (\mu_0 + K) + C_{i-1}^+]$$

$$C_i^- = max[0, (\mu_0 - K) - x_i + C_{i-1}^-]$$

Where: $C^+_0 = C^-_0 = 0$.

K = reference value = $(|\mu_1 - \mu_0|)/2$

μ_0 = the target mean

μ_1 = out-of-control mean we're interested in detecting.

If μ_1 is unknown, set $K = k\sigma$

σ = process standard deviation

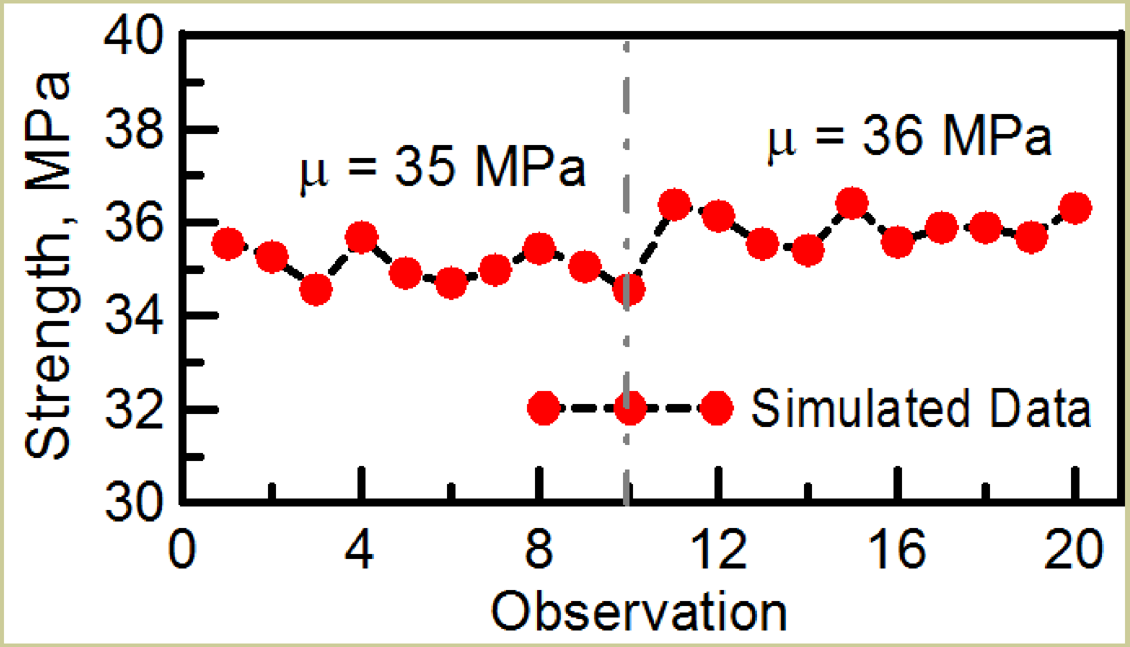
- If the statistics C^+_i or C^-_i exceed a decision value (H) the process will signal out-of-control, i.e. $H = 4\sigma$ or $H = 5\sigma$.

Cumulative Sum (CUSUM) chart

- If an out-of-control point is observed, a search for an assignable cause is in order.
  - Source of assignable causes come from equipment, process steps, operators, or materials (Montgomery, 2008)
- If an assignable cause can be identified, then eliminate the problem and return the process to a state of statistical control
- Resetting signal
  - If the process is in control after some adjustment, the user can decide whether to reset the one-sided upper and lower CUSUMS to zero or not ($C^+_i = 0$ or $C^-_i = 0$) after corrective action

Example-CUSUM chart w&w/o setting signal

- Generate two data sets
  - 20 observations, Standard deviation (σ) =1
  - Change of mean from 35 MPa to 36 MPa at period 11
  - $K = |\mu_1 - \mu_0| /2 = |36 - 35| /2 = 0.5$ Set $H = 4\sigma = 4$
  - Thus, the process has shifted out of control if any of our CUSUM values lie outside above $H = 4$



Calculations of the CUSUM chart

i	x_i	C_i^+	with Zero	C_i^-	with Zero
1	35.6	31.7	31.7	0.0	0.0
2	35.3	34.1	34.1	0.0 C_i^+	0.0
3	34.6	0.0	0.0	17.3	17.3
4	35.7	43.7	43.7	0.0	0.0
5	34.9	0.0	0.0	0.0	0.0
6	34.7	0.0	0.0	2.0	2.0
7	35.0	0.0	0.0	0.0	0.0
8	35.5	21.1	21.1	0.0	0.0
9	35.1	0.0	0.0	0.0	0.0
10	34.6	0.0	0.0	16.2	16.2
11	36.4	115.5	115.5	0.0	0.0
12	36.1	205.4	205.4	0.0	0.0
13	35.6	235.4	30.1	0.0	0.0
14	35.4	250.5	45.2	0.0	0.0
15	36.4	366.4	161.0	0.0	0.0
16	35.6	399.0	193.6	0.0	0.0
17	35.9	463.9	258.6	0.0	0.0
18	35.9	527.3	63.3	0.0	0.0
19	35.7	570.8	106.9	0.0	0.0
20	36.3	677.3	213.3	0.0	0.0

C^+_1 = max [0, x_i – (μ_0+ K) + C^+_0]
= max [0, 35.56– (35+ 0.5) + 0] = 0.06

C^-_1 = max [0, (μ_0- K) – x_i + C^-_0]
= max [0, (35- 0.5) – 35.56 + 0] = 0

1st out-of-control signal at period 14

Without resetting signal

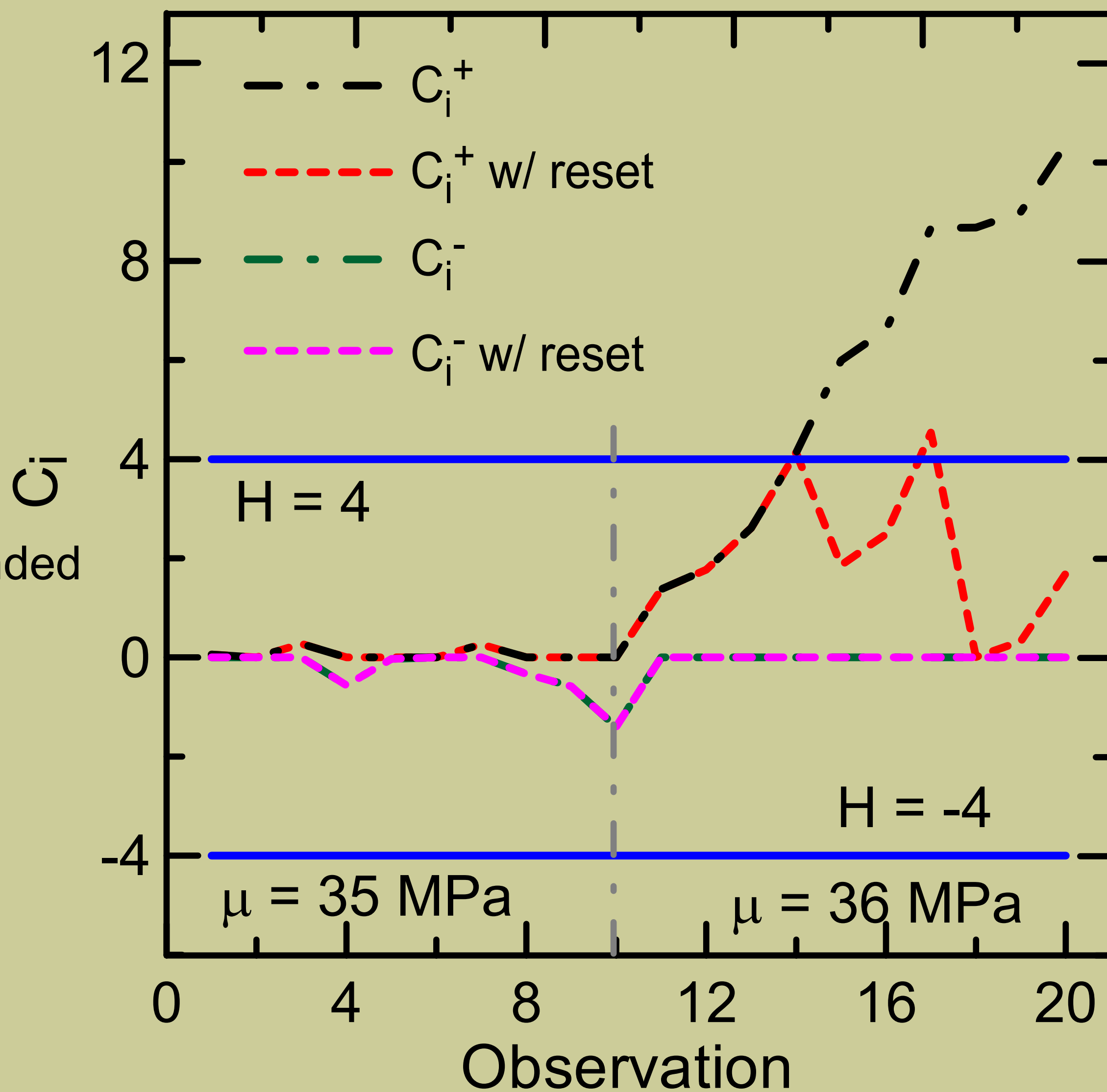
C^+_{15} = max [0, x_i – (μ_0+ K) + C^+_{14}]
= max [0, 37.36– (35+ 0.5) + 4.13] = 5.99

With resetting signal

C^+_{15} = max [0, x_i – (μ_0+ K) + C^+_{14}]
= max [0, 37.36 – (35+ 0.5) + 0] = 1.86

CUSUM chart

- With reset the signal
  - Two out-of-control signals found at period 14 and 17
- Without reset the signal
  - Out-of-control signals founded from period 14 to 20



Exponentially Weighted Moving Average (EWMA) chart, Roberts (1959)

- $z_i = \lambda x_i + (1 - \lambda) z_{i-1}$

- $0 < \lambda \leq 1$ is weight factor assigned to the most current observation

  x_i is the current observation

  z_{i-1} is the previous EWMA statistic with $z_0 = \mu_0$.
- If the process target, $\mu_{0,}$ is not known then the process mean can be used as the initial value
- Values of λ are generally assigned 0.05, 0.1, and 0.2.

Introduction to Exponentially Weighted Moving Average (EWMA) chart

- The center line, upper and lower control limits (UCL and LCL) are defined as:

$$UCL = \mu_0 + L\sigma\sqrt{\frac{\lambda}{2-\lambda}\left[1-(1-\lambda)^{2i}\right]}$$

$$CL = \mu_0$$

$$LCL = \mu_0 - L\sigma\sqrt{\frac{\lambda}{2-\lambda}\left[1-(1-\lambda)^{2i}\right]}$$

where *L* is a multiple of the standard deviation chosen to attain a certain average run length.

- If one or more z_i values fall beyond the upper or lower control limits, then the process is considered to be out of control.

Calculations of the EWMA chart

Number (i)	x_i	EWMA Z_i (λ=0.1)
1	35.56	35.06
2	35.29	35.08
3	35.77	35.15
4	33.94	35.03
5	35.03	35.03
6	34.86	35.01
7	35.76	35.09
8	34.17	34.99
9	34.25	34.92
10	33.69	34.80
11	36.87	35.00
12	35.89	35.09
13	36.34	35.22
14	37.02	35.40
15	37.36	35.59
16	36.12	35.65
17	37.55	**35.84**
18	35.51	**35.80**
19	35.82	**35.81**
20	36.87	**35.91**

- The smoothing weight is selected as 0.1
- z_0 = process target = 35
- For the first period, EWMA statistics is

  $z_1 = \lambda x_1 + (1 - \lambda)\, z_0$

  $= 0.1(35.56) + (1 - 0.1)(35) = 35.06$
- Use L = 3 for λ = 0.1.
- The UCL, CL, and LCL are

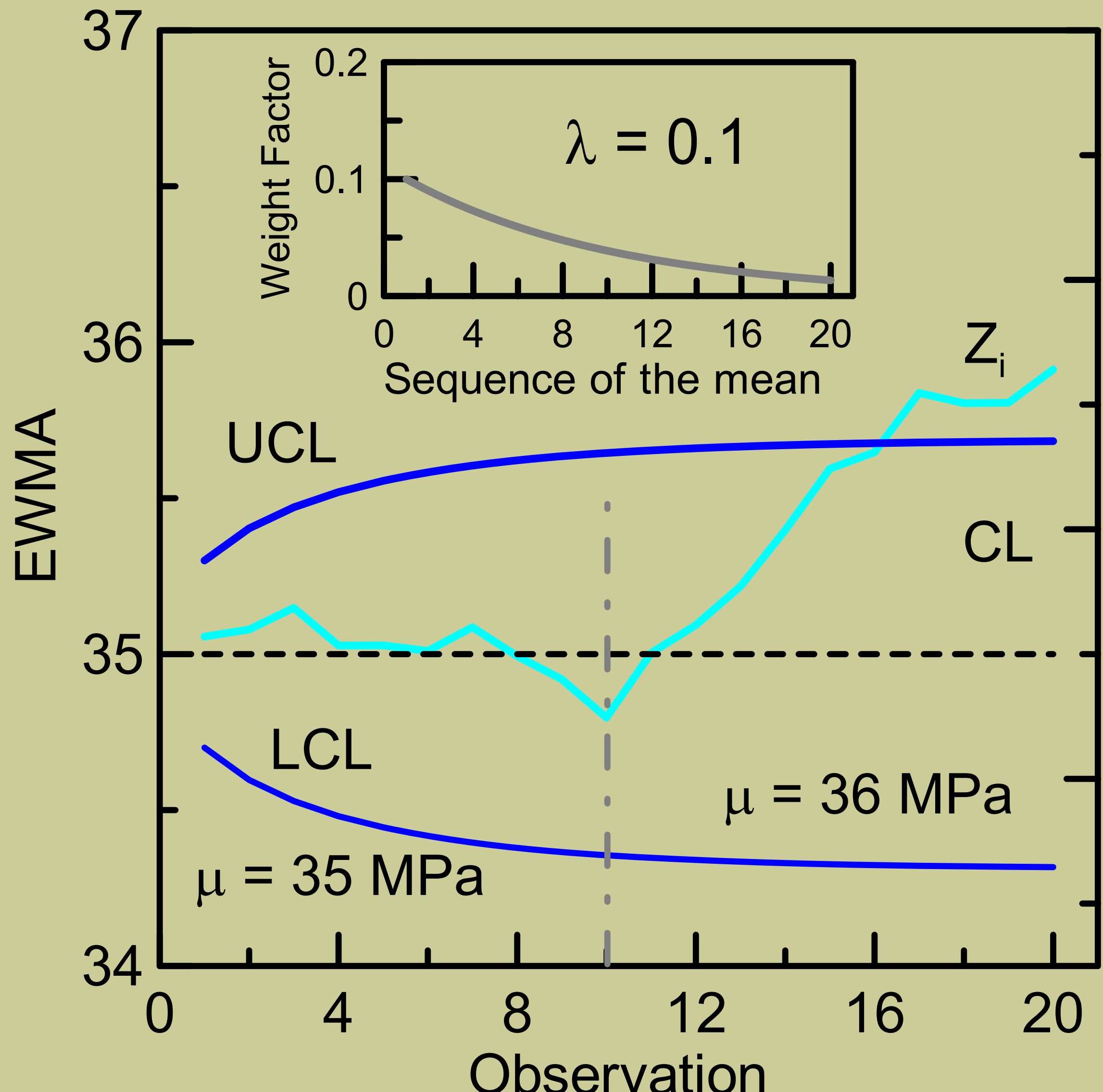
$$UCL = \mu_0 + L\sigma\sqrt{\frac{\lambda}{2-\lambda}\left[1-(1-\lambda)^{2i}\right]} = 35 + 3(1)\sqrt{\frac{0.1}{2-0.1}\left[1-(1-0.1)^{2(1)}\right]} = 35.3$$

$$CL = \mu_0 = 35$$

$$LCL = \mu_0 - L\sigma\sqrt{\frac{\lambda}{2-\lambda}\left[1-(1-\lambda)^{2i}\right]} = 35 - 3(1)\sqrt{\frac{0.1}{2-0.1}\left[1-(1-0.1)^{2(1)}\right]} = 34.7$$

EWMA chart

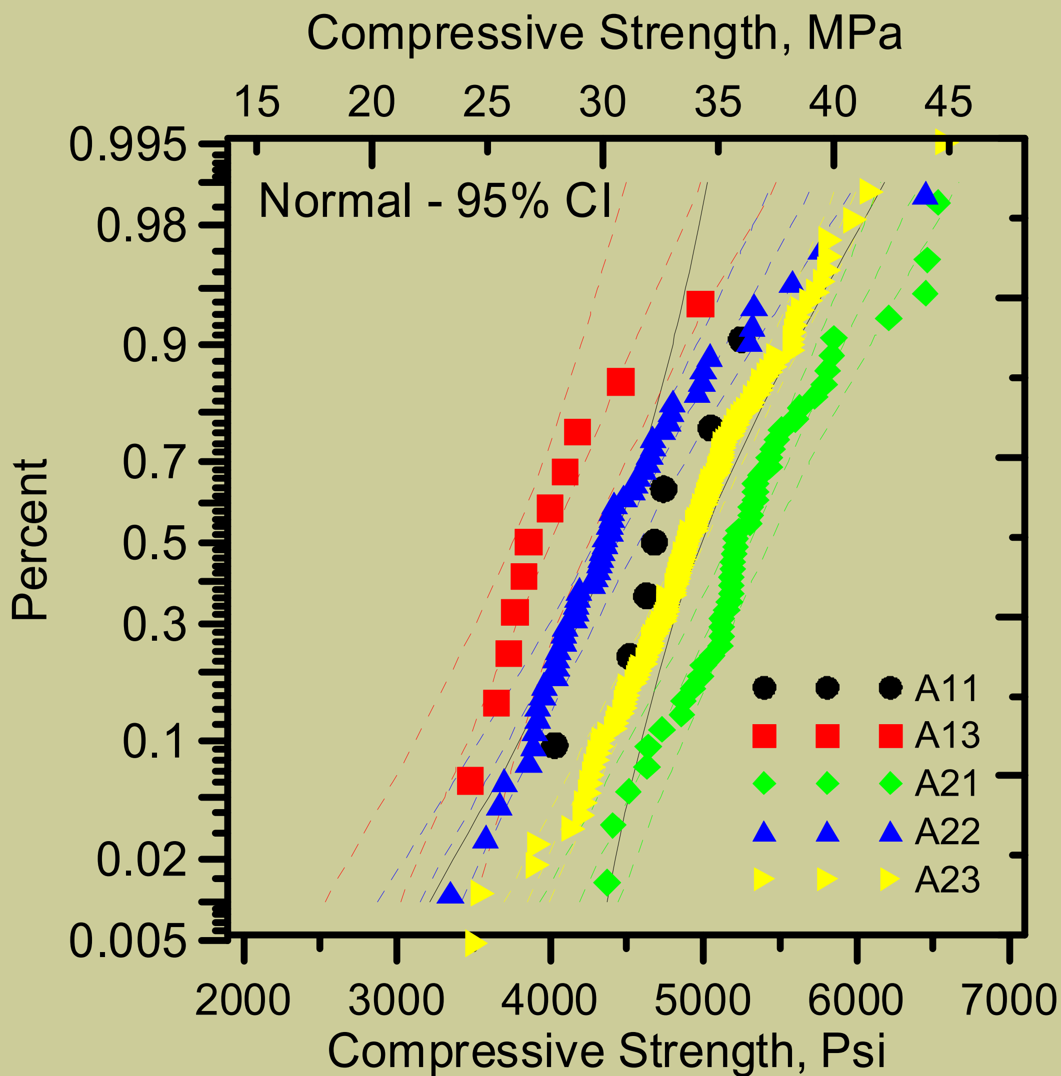
- Out-of-control signals founded from period 17 to 20



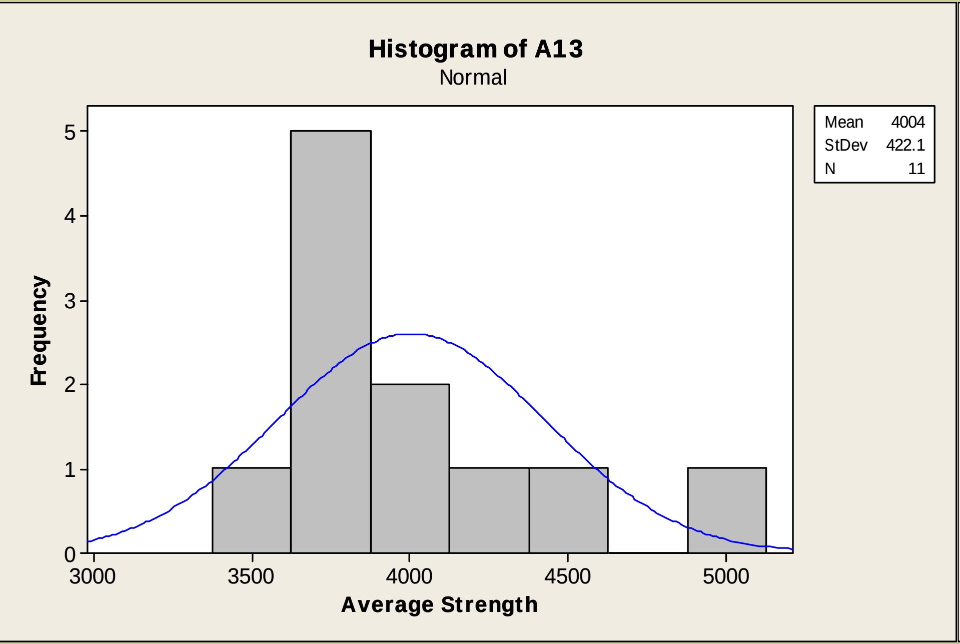
Preliminary Study

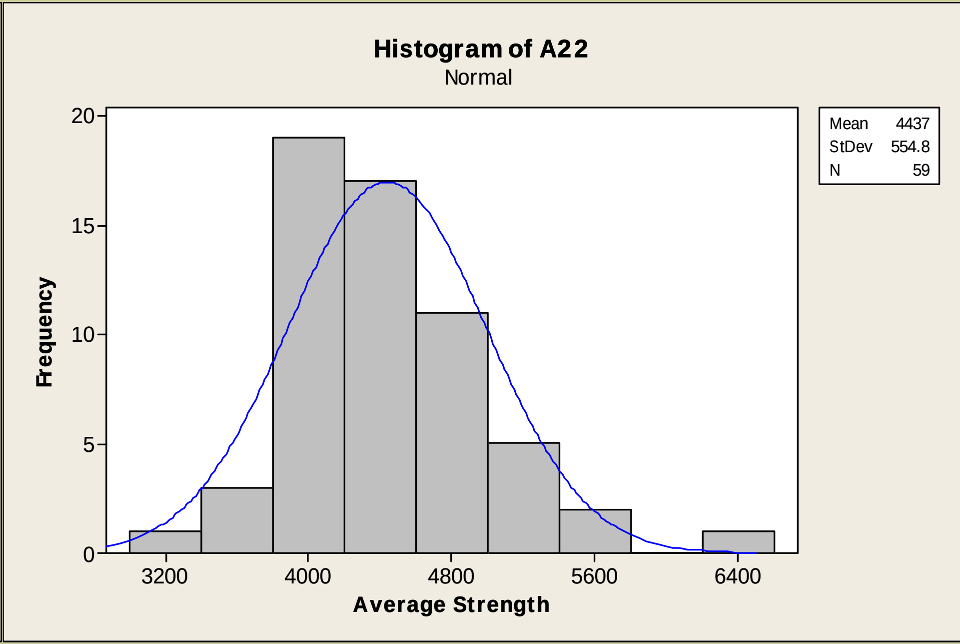
- Several random test cases selected from Arizona Department of Transportation (2006).
  - Five different concrete ready-mix suppliers, two different plants each. For each plant, three separate mix specifications were also selected.
  - The design histories for 28-day concrete strength supplied from these plants were studied.
  - Compressive strength test data from five bridge projects were also randomly selected

Raw Data from different manufacturers, batch plants, concrete grades



Histogram of the selected data sets



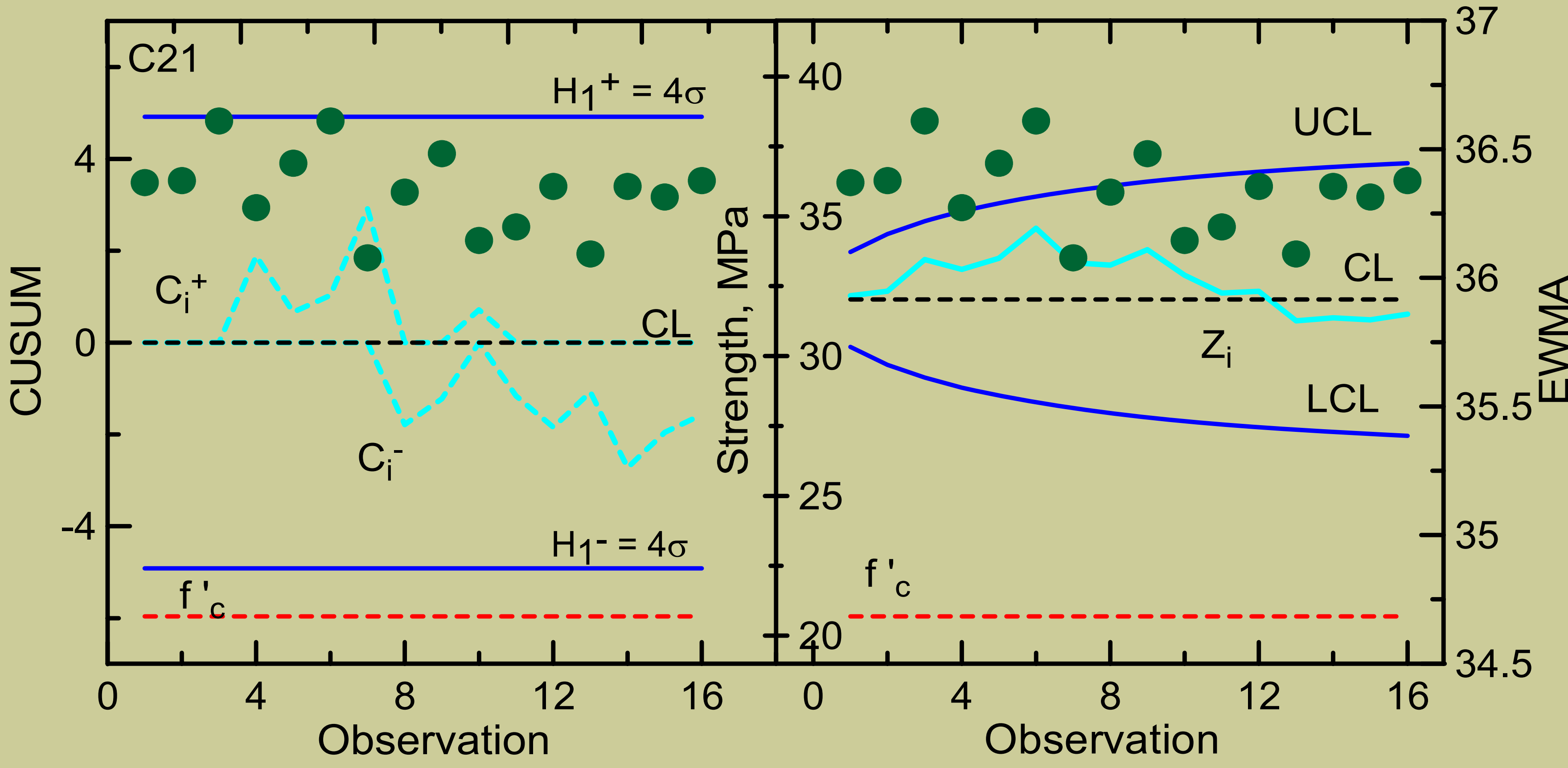


Results

- Classify 4 different scenarios
  - Scenario 1
    - Individual data values are equal to or greater than the lower control limit (in-control process) and no point plots below the f'_c
  - Scenario 2
    - The process is in control and there is a point that falls below f'_c.
  - Scenario 3
    - The individual data values may be less than the lower control limit (out-of-control process), however no point is lower than the f'_c.
  - Scenario 4
    - The process is out of control and there is at least one point below f'_c

Scenario 1
The combined chart of Project C21

- Represent a good process since the process is stable under the acceptable level of concrete strength (greater than the f'_c).
- It does not require any changes in the process

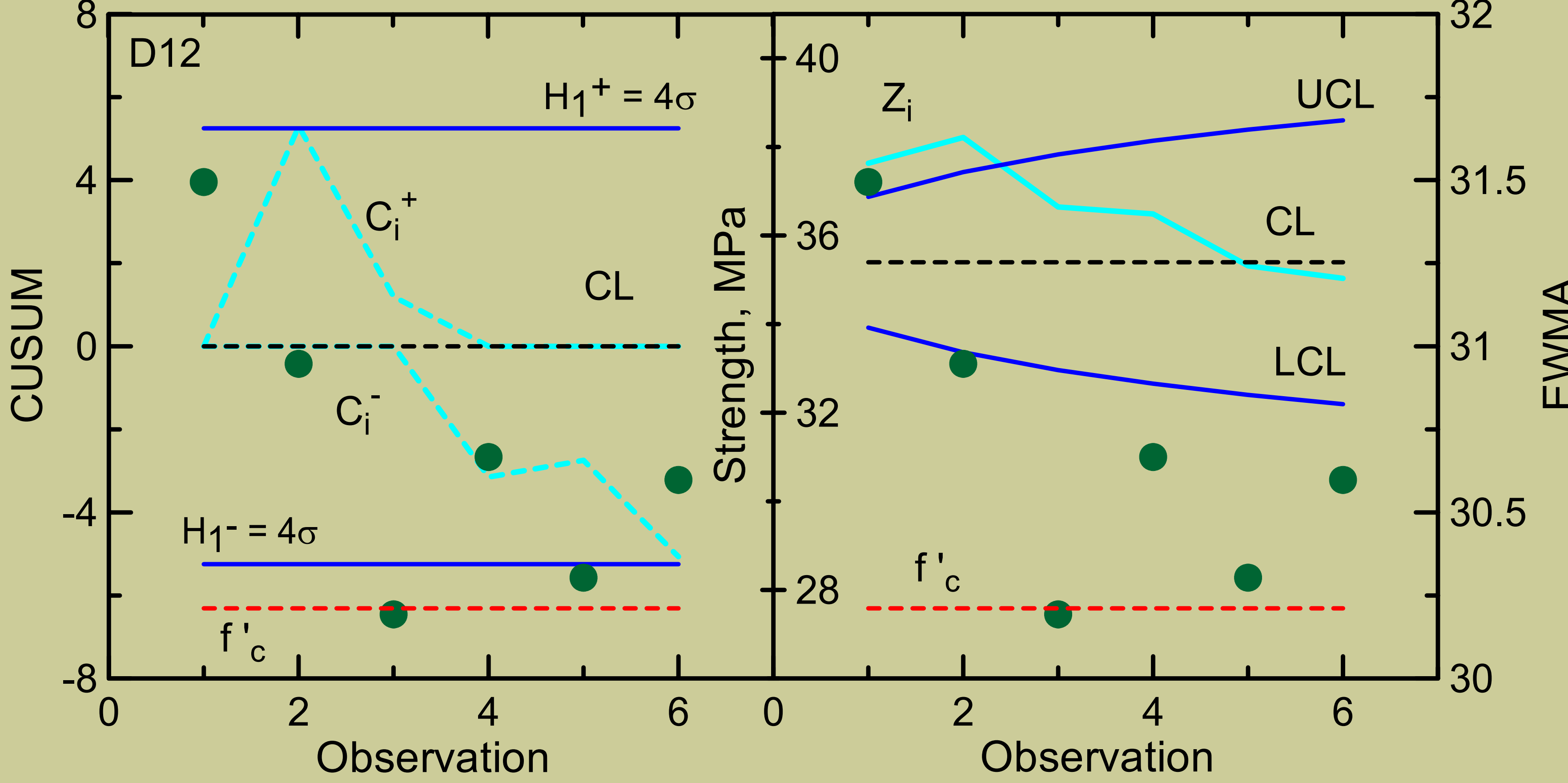


Scenario 1
The combined chart of Project C21

- Based on the summary statistics
  - Average compressive strength (35.90 MPa) is almost 9 standard deviations higher than the minimum specified level (20.7 MPa).
- In this case, the amount of cement in the mixture and the energy used could have been reduced while still meeting the minimum specified level

Scenario 2
The combined chart of Project D12

- Represent a poor process since the process is stable under an unacceptable level of concrete strength (lower than the f'_c)
- It is necessary to inspect the concrete process and find a possible root cause of the problem in order to improve the concrete strength



Scenario 3
The combined chart of Project D13

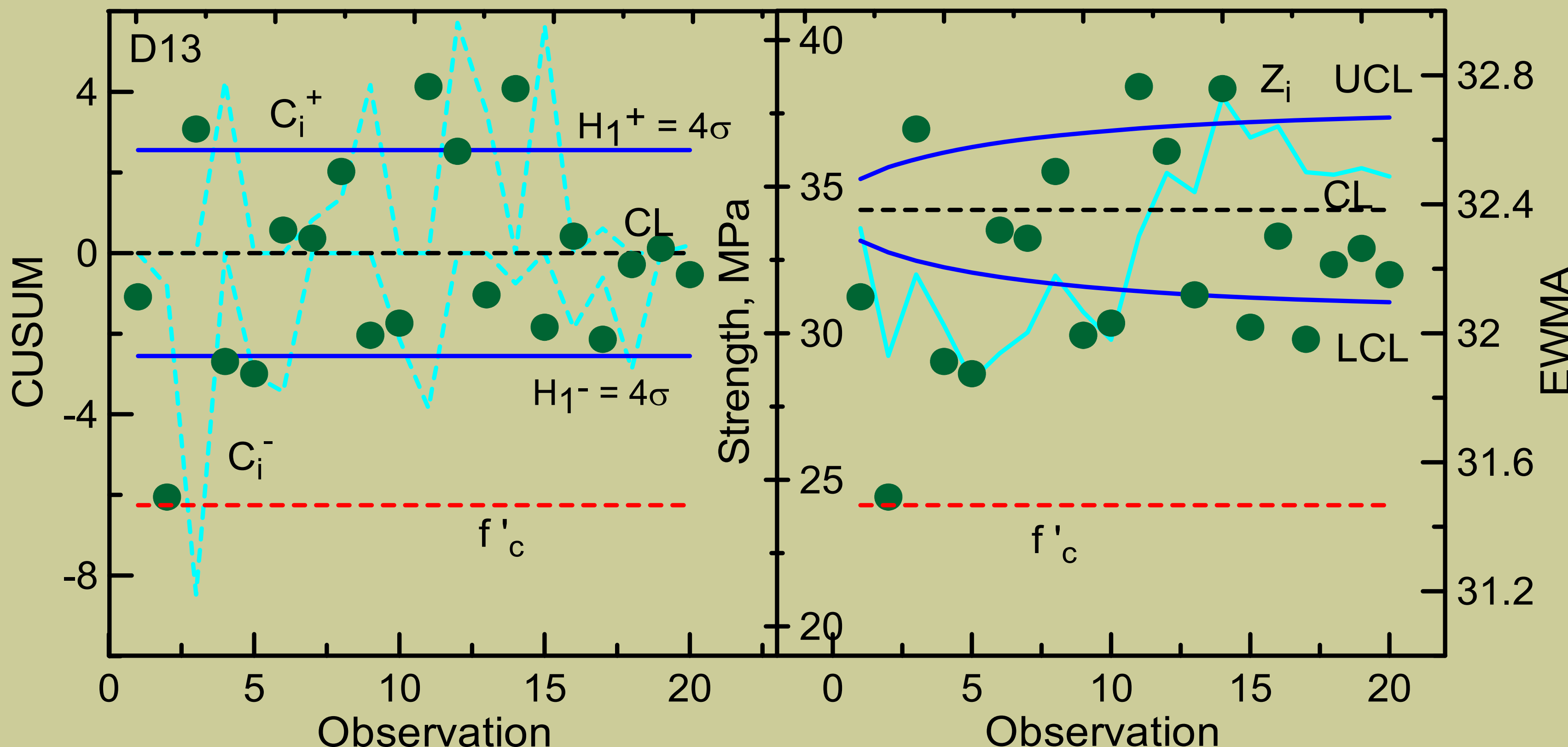
- Example of the first ten observations and calculations of both CUSUM and EWMA charts

No	Strength	f'_c	CUSUM chart				EWMA chart			
			Ci^+	Ci^-	H^+	H^-	Zi	UCL	CL	LCL
1	31.24	24.14	0.00	0.82	2.56	2.56	32.33	32.48	32.38	32.29
2	24.41	24.14	0.00	8.47	2.56	2.56	31.93	32.51	32.38	32.25
3	36.97	24.14	4.26	0.00	2.56	2.56	32.18	32.54	32.38	32.22
4	29.03	24.14	0.00	3.03	2.56	2.56	32.02	32.56	32.38	32.20
5	28.62	24.14	0.00	3.44	2.56	2.56	31.85	32.58	32.38	32.19
6	33.52	24.14	0.82	0.00	2.56	2.56	31.94	32.59	32.38	32.17
7	33.24	24.14	1.35	0.00	2.56	2.56	32.00	32.60	32.38	32.16
8	35.52	24.14	4.17	0.00	2.56	2.56	32.18	32.61	32.38	32.15
9	29.93	24.14	0.00	2.13	2.56	2.56	32.07	32.62	32.38	32.14
10	30.34	24.14	0.00	3.85	2.56	2.56	31.98	32.63	32.38	32.14

- Summary Statistics (n = 20)
  - The average compressive strength = 32.38
  - The standard deviation = 0.64
  - CUSUM chart : Set k = 0.5, so K = 0.32
  - EWMA chart: Use L = 3 and λ = 0.05

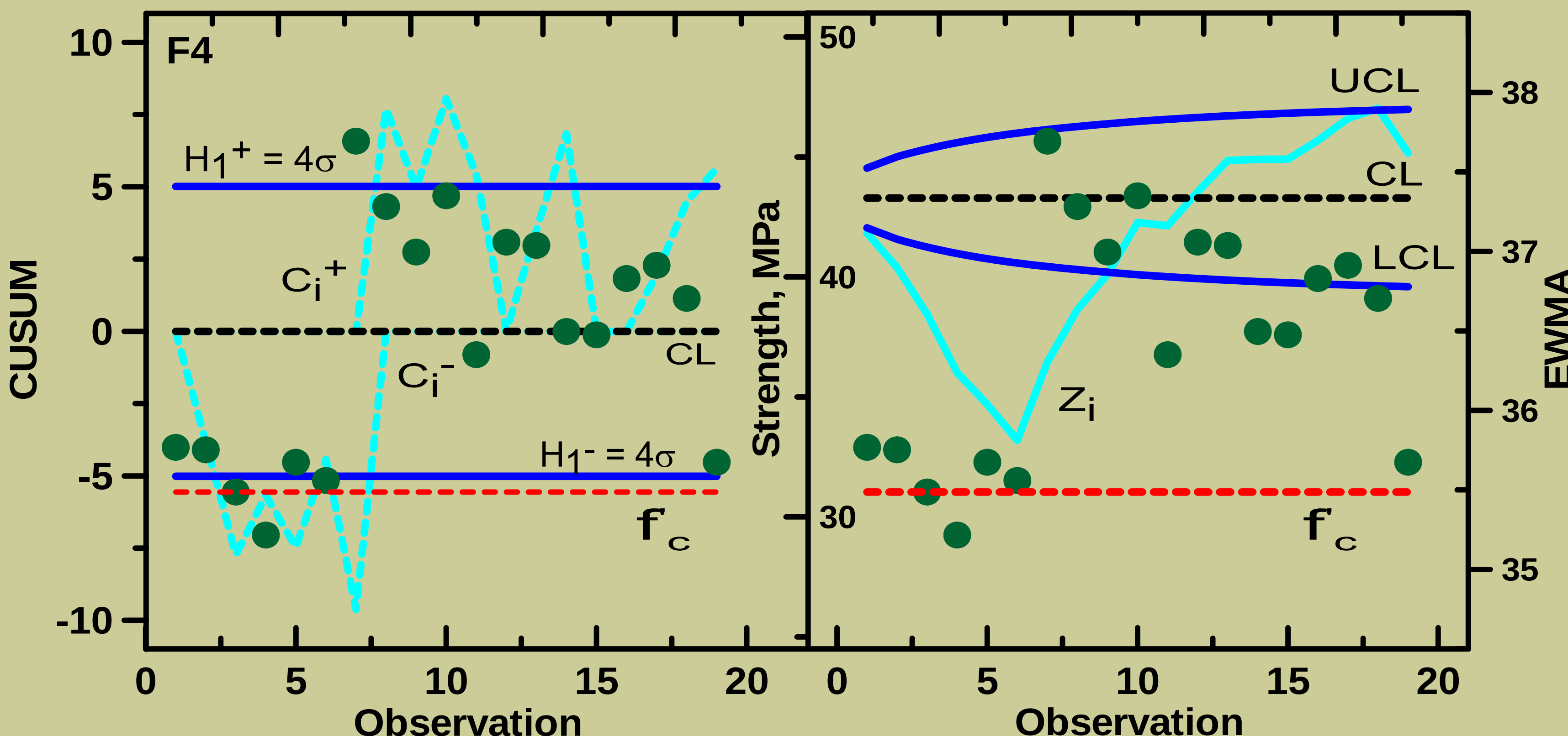
Scenario 3
The combined chart of Project D13

- Represents an acceptable process. Although not stable, but it maintains an acceptable level of concrete strength (greater than the f'_c)
- Investigated to determine if it really is out of statistical control and find an assignable cause or if the signal was a false alarm



Scenario 4
The combined chart of Project F4

- Represent a poor process that is not stable and has an unacceptable level of concrete strength (lower than the f'_c)
- Investigate the process and reduce variation with the goal of bringing it back into statistical control (stability) and make it capable.



Result summary

- The test cases are classified to 4 scenarios when monitor by 4 different combined control charts

Combined control chart	EWMA		CUSUM	
	L = 3 and λ = 0.05	L = 3 and λ = 0.1	h = 4 and k = 0.5	h = 5 and k = 0.5
$x_i > f'_c$ In-control process	B13, A11, and C21	B13, A11, and C21	B13, B21, C21, and E22	B13, B21, C21, and E22
$x_i < f'_c$ In-control process	D12 and E23	D12 and E23	D12	D12
$x_i > f'_c$ Out-of control process	A13, A23, B21, C12, C22, D13, E13, E21, and E22	A13, A23, B21, C12, C22, D13, E13, E21, and E22	A11, A13, A23, C12, C22, D13, E13, and E21	A11, A13, A23, C12, C22, D13, E13, and E21
$x_i < f'_c$ Out-of control process	B22, C11, C13, D11, F1, F2, F3, F4, and F5	B22, C11, C13, D11, F1, F2, F3, F4, and F5	B22, C11, C13, D11, E23, F1, F2, F3, F4, and F5	B22, C11, C13, D11, E23, F1, F2, F3, F4, and F5

Discussion

- The combined CUSUM-run chart is a good choice for monitoring small shifts in the process mean
- CUSUM scheme is appropriate for producer's perspective because it shows the stability of the process mean.
- The run chart represents the consumer's needs by comparing the strength to minimum acceptable level, f'_c, in order to decide whether to accept or reject the sample
- These two control charts complement one another. Combining the run chart with the CUSUM chart can identify an abnormal process if the CUSUM chart fails to detect the shifts in the process mean or vice versa (Scenarios 2 and 4).

Future challenges

- How do we handle multiple parameter monitoring and specifications based on multiple criteria.
- Meet two conditions of parameter A, and parameter B meeting their own criteria and standards?
- Compressive strength and durability criteria
- Compressive strength and flexural strength
- Strength and permeability
- Strength and maturity

Conclusion

- If the producer had control charts on some of the processes that resulted in the test cases used in this study, unusually high or low strength levels may have been identified early in the process, corrective action taken, and significant reductions in rejected lots or excessive amounts of cement used would have been avoided.
- In the case of the average is much higher than the minimum specified level, the amount of cement in the mixture and the energy used could have been reduced by using the quality control charts while still meeting the minimum specified level.

Acknowledgements

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