Advanced statistical control technique for environmental concrete production

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Concrete is one of the fundamental construction materials used today, the vast majority of which is based on Portland cement. Increasing environmental pressures due to the huge CO_2 burden associated with Portland cement manufacture requires that new fuel technologies and production techniques are explored.

For environmental, economic and business reasons there is also a requirement that concrete is produced with as little excess Portland cement within the concrete as possible. This, together with the change in emphasis in the British Standard from proscribed to described concrete's has allowed for a change in both the methods of concrete production and statistical plant control. The changes allowing custom designed concrete's which have specific attributes and characteristics has raised the possibility that new and more stringent mathematical control of concrete production plants is required. Traditionally, this has globally been through the CUSUM method.

This paper describes a new method of production control, which allows the simple operation of multiple plants with multiple concretes. The new model for plant control has been termed the HUNT model as the model uses mathematical control relationships to actively hunt for the correct cement content of the nucleus.

Complications occur with CUSUM controlled concrete production when the moisture content, particle size and distribution, shape and flakiness of the aggregates and sand varies. Larger stone generates a lower slump concrete as does extra dust or low moisture contents of the stone. Conversely, wet stone or sand produces more fluid or more workable high slump concrete.

Stone is a natural material and one face in a single quarry will continually produce slightly different material, stockpiling of the stone prior to use also starts to separate the different particle sizes. Weather changes will also produce different moisture contents within the stockpile, as rain will percolate down to the bottom of the pile while dry weather will desiccate the surface layers of the stockpile leaving a wet core within the stockpile. Loading of stone into a concrete plant and draining the stone into the mixers will further separate the stone into bands of single sizes.

Traditionally, these can cause the CUSUM method to predict higher or lower strengths than would normally be expected. Generally, these abnormal concretes are not included in CUSUM monitoring, should these concretes be used, incorrect future strength prediction are made and in the case of higher strengths, subsequent reduction of the cement content of the nucleus. Post change concrete's based on this CUSUM derived Portland contents would then be in danger of failing to meet the design strength. Incorrectly predicted lower strengths would cause the concrete to be cement rich, environmentally and economically non-viable.

It is proposed that there is a simple assumption linked to the internal structure of concrete, which can be applied, to the target concrete allowing the mathematical models to predict realistic performance strengths regardless of concrete variation and thus modify concrete design and production accordingly. The mathematical basis of this assumption is termed the HUNT model.

The HUNT model uses the water: cement ratio relationship to predict physical performance. And a slump curve to predict water: cement ratios of production concrete. Using this model for a known concrete family with a known cement content, and using the water: cement ratio and slump curve, it is possible to predict the strength at any slump directly without conversion back to the main relationship curve.

The initial concept of the HUNT model is that the 7 and 28 day strength of a concrete can be predicted from the following assumption :- The overall strength of the concrete depends on the inter particular distance between the stone components and the density of the CSH Gel. Initially this may appear to be a huge oversimplification, however, when empirically applied to a real production environment The HUNT model accurately predicts the final concrete performance. The HUNT model can also be directly applied to a family of concretes without having to convert back through the main relationship curve to the characteristic concrete.

It has been known in the past that supplying the concrete towards the lower limits of the slump range will produce a concrete which is less likely to fail. Use of this concrete in the CUSUM calculation would cause the plant to appear to be running cement rich and lead to false confidence. Under the HUNT model, Low slump concrete would be required to meet a higher strength than the design due to the low slump.

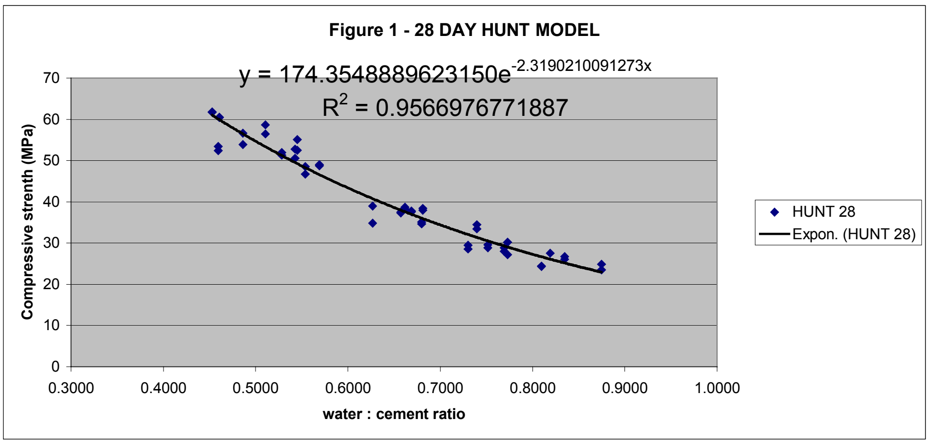


Figure 1 - 28 DAY HUNT MODEL

EN 206 uses the concept of families of concretes. The HUNT model can be readily applied to this concept as the design of a family of concretes obeys the w/c relationship curve central to the HUNT calculation. This concept has been empirically tested on over 150,000 m-3 of concrete produced in an 18 month period.

Unlike the CUSUM model, the HUNT model does not suffer from auto correlation allowing high sample rates and a range of concrete strengths and slumps to be used directly within the control calculation.
The graph below shows the HUNT model relationship for a family of concrete's based on oven dried aggregates, the strength of that family is directly related to the water: cement ratio and follows a simple exponential curve.

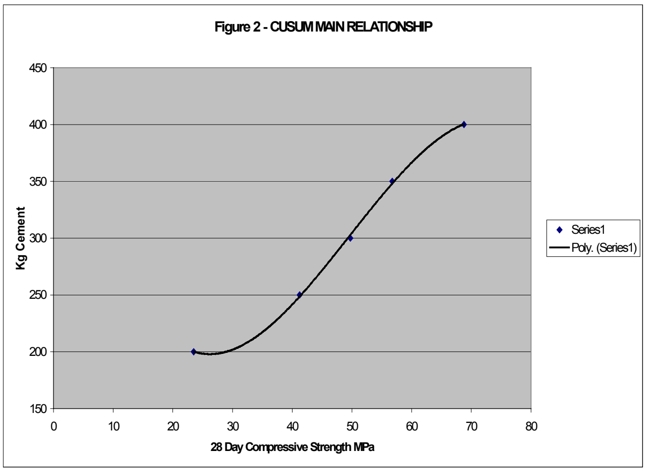


Figure 2 - CUSUM MAIN RELATIONSHIP

Normal design criteria for a concrete family are followed according to the BS8500 and EN206 standards. The composition values of the family design are recorded as polynomial equations as is the slump curve for a control concrete. The water : cement ratio is then plotted for each member of the family against strength, this forms a 28 day family relationship exponential HUNT model curve (Fig 1) rather than the cement : strength main relationship used in CUSUM (Fig 2) . This curve is valid for all cement contents and slumps for the family.

The complications generated by dry, dusty or irregular stone producing low slump can be related back to the apparent water : cement which would have "normally" generated the low slump. According to the HUNT model curve the lower water : cement ratio would predict a higher strength for the concrete. This strength prediction is then used for conformity testing.

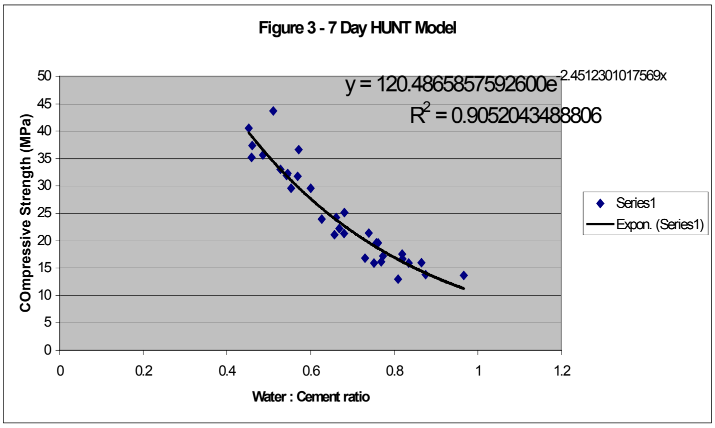


Figure 3 - 7 Day HUNT Model

The HUNT model also uses a 7 day family relationship exponential HUNT model curve (Fig 3) obtained in the same manner as the 28 day model curve. The relationship between the 28 day curve and 7 day curve is obtained as a second curve and is used to predict the 28 day strength from the 7 day value.

The HUNT model is a dynamic model and as such the strength data from empirical conformity testing is fed into the model to refine the curve and relationship data. In this way the curve continuously self refines unless there is a change within the performance of the concrete which is not part of the normal variation within the production regime. Each conformity period initially uses the previous curve generated by the previous conformity period so that continuity is maintained during the early part of a conformity period.

The model curves are continuously used to re-calculate the cement content values required to produce concrete with the desired compressive strength, in this way the model self adjusts the concrete designs to maintain the desired values. As part of the plant control, the HUNT model calculates the cement contents required to reach the required strength for each family member by producing a Cement to MPa conversion equation for S2 concretes.

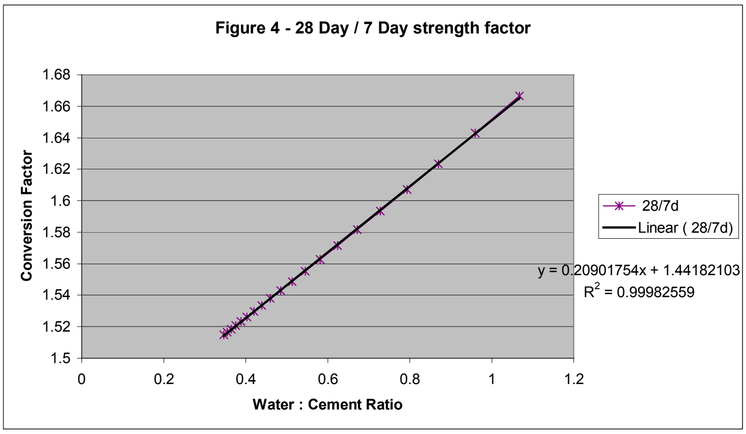


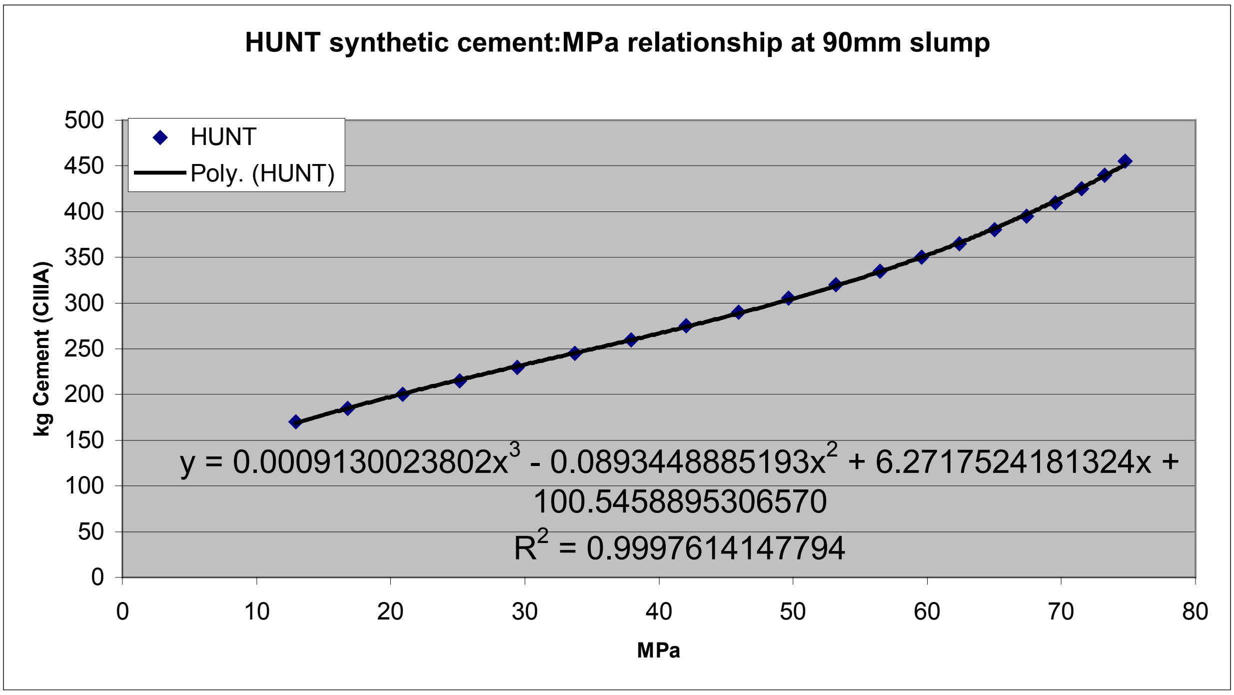
Figure 4 - 28 Day / 7 Day strength factor

The British standards require that a safety buffer of 3x the plant standard deviation for the standard family – 4MPa be employed. Thus for a plant with a SD of 4, an S2 C35 class concrete would need to be targeted at 35 + (3*4-4) = 43 MPa. Also as the S2 class has a maximum slump of 90 mm.

28 D Strength predictor 174.3549 -2.31902

7 D Strength predictor 111.5454 -2.27805

		SLUMP 70 mm						Slump 90			
CEM	WRA	Water	W/c	7 D	28 D	7/28d	28/7d	extra	water	W/C	28D
170	850.0	183.16	1.08	9.58	14.33	0.67	1.50	7.61	190.76	1.12	12.92
185	925.0	179.22	0.97	12.28	18.44	0.67	1.50	7.50	186.71	1.01	16.79
200	1000.0	175.56	0.88	15.10	22.77	0.66	1.51	7.41	182.96	0.91	20.90
215	1075.0	172.18	0.80	17.99	27.22	0.66	1.51	7.33	179.51	0.83	25.15
230	1150.0	169.10	0.74	20.90	31.69	0.66	1.52	7.27	176.36	0.77	29.46
245	1225.0	166.31	0.68	23.76	36.12	0.66	1.52	7.21	173.51	0.71	33.74
260	1300.0	163.81	0.63	26.55	40.45	0.66	1.52	7.16	170.97	0.66	37.95
275	1375.0	161.60	0.59	29.25	44.63	0.66	1.53	7.12	168.72	0.61	42.03
290	1450.0	159.70	0.55	31.82	48.62	0.65	1.53	7.08	166.78	0.58	45.94
305	1525.0	158.10	0.52	34.25	52.41	0.65	1.53	7.05	165.14	0.54	49.67
320	1600.0	156.80	0.49	36.53	55.97	0.65	1.53	7.02	163.82	0.51	53.19
335	1675.0	155.80	0.47	38.67	59.30	0.65	1.53	7.00	162.80	0.49	56.49
350	1750.0	155.12	0.44	40.64	62.38	0.65	1.53	6.97	162.09	0.46	59.57
365	1825.0	154.75	0.42	42.46	65.23	0.65	1.54	6.95	161.71	0.44	62.41
380	1900.0	154.70	0.41	44.13	67.83	0.65	1.54	6.94	161.63	0.43	65.02
395	1975.0	154.96	0.39	45.64	70.20	0.65	1.54	6.92	161.88	0.41	67.40
410	2050.0	155.54	0.38	47.00	72.34	0.65	1.54	6.91	162.45	0.40	69.57
425	2125.0	156.44	0.37	48.23	74.25	0.65	1.54	6.90	163.34	0.38	71.51
440	2200.0	157.67	0.36	49.31	75.95	0.65	1.54	6.89	164.56	0.37	73.24
455	2275.0	159.23	0.35	50.26	77.44	0.65	1.54	6.88	166.11	0.37	74.78



The polynomial curve derived above is then used to generate the plant settings automatically

Kg Cement = 0.0009130023802*(MPa^3) - 0.0893448885193*(MPa^2) + 6.2717524181324*(MPa) + 100.5458895306570

I.E.

hunt	SD	4		Plant
	MPa	PREDICTION	Current	Change
C10	15	177.6	193	-16
C15	23	206.8	211	-4
C20	28	226.2	229	-3
C25	33	243.0	247	-4
C30	38	260.0	265	-5
C35	43	277.6	284	-7
C40	48	296.7	304	-8
C45	53	317.9	327	-9

The Hunt model is then used to check the C35 prediction.

		SLUMP 70 mm						Slump 90			
CEM	WRA	Water	W/c	7 D	28 D	7/28d	28/7d	extra	water	W/C	28D
277.6226	1388.1	161.25	0.58	29.70	45.34	0.66	1.53	7.11	168.36	0.61	42.72

The output from the model can then be used to generate the plant mix designs and maintain the conformity of the plant at minimum cement levels.

Discussions

The hunt model can control multiple concrete designs and cement combinations by deriving control factors for each concrete family. The ability to use a simple spreadsheet which tests each compressive strength value on entry against the statistical variation experienced at that plant enables site specific non technical staff to9 monitor day to day fluctuation. Trend analysis can also be employed to monitor permanent changes with the production performance

Appendix 1 - Example of the HUNT calculation for a concrete.

Production Date	18/8/04
Concrete	C40 S2 CIIIA 20mm WRA
Ordered quantity	2.8 m3
Target slump	50 mm
Achieved slump	15 mm

Achieved 7 day Compressive strength	37.42 MPa	
Achieved 28 day Compressive strength	60.43 MPa	60.51 MPa

HUNT model prediction

Cement content	304.4 kg
S2 (70 mm) Water content	158.15 L

Obtained from S2 model calculation
(= 0.000000129213*(304.4^3) + 0.000557667669*(304.4^2) - 0.42298936938*304.4 + (246.813760321432-(1522g [admix]/100))

W:C ratio = 0.52

S2 slump modification to 50 mm

=(0.3265*(50-70) + (158.15/304.4)

W:C = 0.50

28 day, 50 mm slump prediction

= $165.323717e^{(-2.201468366*0.5)}$

= 55.22 MPa

S2 slump modification to actual slump

=(0.3265*(15-70) + (158.15/304.4)

W:C = 0.461

28 day, 15 mm slump prediction

= $165.323717e^{(-2.201468366*0.461)}$

= 59.98 MPa

7 day, 15 mm slump prediction

= $111.5454453e^{(-2.278047038*0.461)}$

= 39.07 MPa

Model agreement

28 Day average empirical strength = (60.43 MPa + 60.51 MPa)/2 = 60.47 MPa

7 Day empirical strength = 37.42 MPa

Empirical standard deviation from conformity period data set (48 cubes) to model = 2.47 MPa

7 day difference = 37.42 –39.07 = -1.65 MPa (not statistically significant)

28 day difference = 0.49 MPa

Concrete conforms to design.