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Effects of Moisture Variation on Concrete Mixes and Methods to Control Final Mix Quality

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Abstract

Moisture in aggregates can be difficult to control and can cause large variations in the consistency of the concrete mix being made. This in turn can lead to problems with the final mix which in turn causes final product quality problems meaning waste of materials and extra costs of raw materials. This paper details the effects of this variation and explains methods of controlling the quality of the concrete.

One Ready Mix Concrete producer in Europe undertook extensive testing and determined that a cost saving of USD2.94 per m³ could be achieved using moisture control. This gives a very fast Return On Investment for the equipment and has the added benefits of higher quality concrete and more efficient production. Even a modest concrete producer can pay for the capital investment within a few months.

1. Introduction

Concrete is made from a mix of materials including aggregates, cement and water. The concrete hardens as a result of the interaction between the water and the cement, and a difference in the ratios of these has a direct influence on the final strength of the concrete mix as shown in Figure 1.

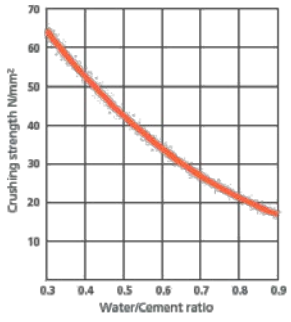


Figure 1: The relationship between the concrete strength and the W/C ratio

2. The problem with moisture

2.1 Material measurement

In a concrete batch plant the raw materials are normally stored in stock piles in a goods yard. This stock is naturally affected by the local weather conditions and so can increase in moisture when it is raining and decrease when the weather is good.

This moisture variation even occurs if the raw materials are in covered storage areas because sand and aggregates are free draining materials so moisture can vary throughout the storage pile.

When concrete mixes are made, the raw materials are generally measured by weight. This weight includes the dry weight of the materials and also the weight of any water that is present in the material.

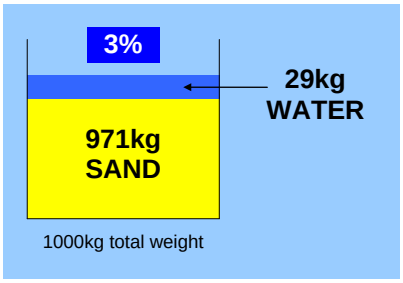


Figure 2: Example of 1000kg of sand at 3% moisture

2.2 Effects of moisture variation

The variation in moisture in the raw materials leads to two effects in the mixer itself. The first is that the dry weight of raw materials in the mix is less than that specified (if the mix design is calculate with dry weights) and the second is that there is an unknown amount of extra water in the mixer that has not been accounted for in the mix design.

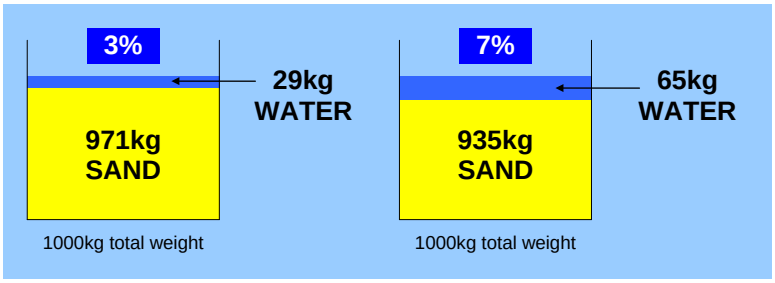


Figure 3: The difference in dry material weight

The lack of dry material in the mix leads to an under-yield in the final mix and means that where, for example, 1m³ of concrete has been specified, only 0.9m³ is achieved. This can mean that a precast manufacturer's moulds do not get completely filled or not enough concrete is delivered to a Ready-Mix customer.

Under yielding also decreases the efficiency of the cement as this is based on a set amount of dry material being in the mixer to make a certain size mix.

Where a concrete is made from multiple raw materials (for example, from Sand, Gravel and larger stone), moisture variations in each of the raw materials will be different and this will lead to variations in the proportioning of the materials. This can cause changes in the consistence, appearance and overall quality of the concrete.

If colours are being used, then the difference in the proportioning of the raw materials can lead to variations in the colours of the final product as the surface area of the materials in the concrete changes.

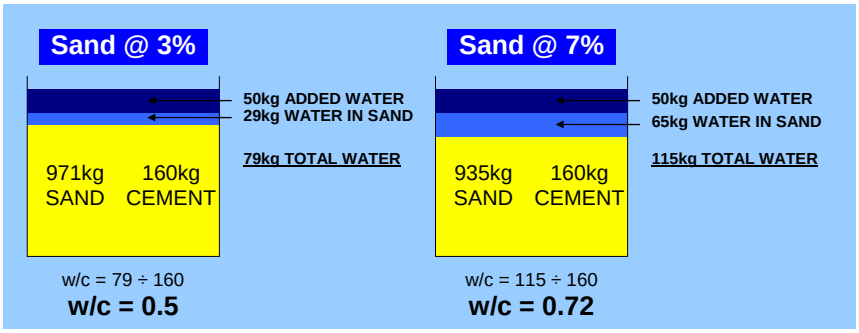


Figure 4: How moisture affects the water/cement ratio

The extra moisture in the raw materials causes variation in the water/cement ratio and this has a direct relationship with the final compressive strength of the concrete as shown in Figure 1.

Many plant operators will see the variations in the moisture as changes in the workability or consistence of the concrete mix whilst it is in the mixer, and will correct for this during the production. However, this is not good practice as this means that the water is added based on a very subjective viewpoint. This makes it more difficult to get a consistent product from a number of operators.

Material	Design Weight	Actual Weight Variation of 1.0%	Water
Cement	350	350	0
Sand and Aggregates	1900	1881	19
Water added in mixer	175	175	175
Total Weight	2425	2406	194

Table 1: A typical batch made with moisture variation of 1.0%

Table 1 shows a typical batch made with moisture control which is accurate to 1.0% moisture. The total water in the mix is 194kg. The design water/cement ratio is 175/350 = 0.5 whereas once the mix has been completed, the actual water/cement ratio is 0.55.

This means that the strength of the concrete is lower than designed or that more cement needs

to be added to correct the water/cement ratio. The total cement needed can be calculated by 194 / 0.5 = 388kg so and extra 38kg of cement is needed to compensate for the extra water.

Material	Design Weight	Actual Weight Variation of 0.2%	Water
Cement	350	350	0
Sand and Aggregates	1900	1896	4
Water added in mixer	175	175	175
Total Weight	2425	2406	179

Table 2: The typical batch made with moisture variation of 0.2%

Table 2 shows the same mix design made with a moisture variation of 0.2%. This gives a total water value of 179kg which gives the actual water/cement ratio as 0.51. Again if the calculation is reversed to give the correct water/cement ratio, it is shown that the total cement needed is 179/0.5 = 358kg, so an extra 8kg of cement is needed.

Comparing the two mixes made, by reducing the variation in the aggregate moisture to 0.2% from 1.0%, it is possible to save 30kg of cement per batch.

Accurate on line moisture measurement equipment used with a good control method can reduce the moisture variation to 0.2%.

2.3 Overdesign

Normally the cement is not changed in this way, but the variation in the batch moistures is handled using statistical analysis performed on batches already made.
The standards defined by the European government mean that a concrete manufacturer in Europe is obliged to guarantee the target strength for a customer taking into account any potential variation in strength.

To do this, the concrete mix is overdesigned (i.e. made to a higher strength than needed) so that in the worst case it will still be within the strength limits required by the specifier.
The statistical term Standard Deviation is a measure of how wide the spread of a number of points is around an average value. 95% of points will be within 2 Standard Deviations of the average.

As an example, statistics will show that a batch plant over time will manufacture batches of C30 (30N/mm²) specification concrete with a Standard Deviation of 5N/mm². The European standards specify that Ready-Mix Concrete must be overdesigned by twice the Standard Deviation (so 10N/mm² in this case) so the C30 mix design is calculated to give an average strength of 40N/mm².

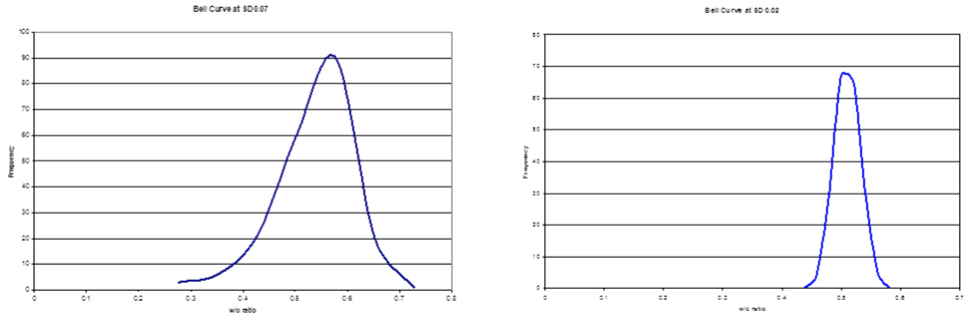


Figure 5: Two Statistical Deviation graphs showing poor and good control

This means that by reducing the number of spread of the variation in their concrete strength tests, concrete producers can reduce the design strength of their concrete mixes for the same specified concrete. This means that less cement is used in the mix design of the concrete and so the costs are less. As moisture is the biggest variable in the mix design, controlling the moisture of the concrete batches is an important part of reducing the variation.

3. The solution with Moisture Control

3.1 Sand and Aggregate Measurement

Moisture is measured continuously in the sand and aggregate bins by accurate moisture sensors that are calibrated to read dry based moisture values. This value can then be used in the control system to adjust the target weight of the material.

Calibration
In order to work effectively, the moisture sensors first need to be calibrated to the material they are measuring. This is a critical part of the installation and commissioning of the sensors and can cause problems if not done correctly. Calibration is a simple process of taking a number of raw readings from a moisture sensor whilst samples are being collected of the material being batched. These samples should then be tested using a laboratory test and the result matched to the raw readings. Although calibration can be achieved with two points, it is better to have a multiple point calibration as is allowed in some calibration software. If the software can only accept two calibration points, it is possible to use tools such as Microsoft Excel to perform the multi-point calculations.

The only accurate moisture test is to take each sample of material and weigh it, then to bake it in an oven and re-weigh it. The loss in weight is the weight of water in the material, and this can be used to get the dry-based moisture value using the following equation:

$$M = \frac{W_{wet} - W_{dry}}{W_{dry}}$$

Where M is the moisture, W_{wet} is the wet weight and W_{dry} is the dry weight.

It is important to carry out the laboratory test as accurately as possible, using weighing equipment which is accurate to 0.1kg in 5kg and making sure that the oven baking has been performed for long enough (this can be done by placing the sample of material in to the oven

again and repeating this until there is no further loss in weight). If used with good quality moisture sensors, then this calibration process will be accurate to 0.2% (in sand) over the entire working range of the aggregate. If the material being measured does not change then a good microwave moisture sensor will not need recalibration for the life of the sensor provided that it is fully temperature compensated.

Batching

During the batching process, it is important to make an average measurement of the material being measured as the moisture may vary a lot within a stockpile of sand or aggregate. This average should then be used to adjust the target weight to account for the weight of water held in the material.

Calculations

As an example, a typical batch process may weigh 75% of the total weight and then use the value from the moisture sensor to then recalculate the original target using the following equation:

$$T_{new} = T_{old} + \frac{T_{old} \cdot M}{100}$$

Where T_{new} is the new Target, T_{old} is the original target and M is the calibrated moisture value from the sensor.

So as an example, if you are weighing 1000kg at 5% moisture then the New Target should be calculated as follows:

New Target = 1000 + 1000 * 5/100 = 1050kg

Mixer Control

Whilst it is possible to just use probes in the raw materials to calculate the amount of water going into the mixer, it is sometimes more practical to measure in the mixer as well.

To control the final moisture from the raw materials a lot of care must be taken to prevent extra moisture from entering the mixture after the initial weighing. It is also important to measure in all of the raw materials being used in the mix design for best results.

To simplify the calculations, this document will concentrate on controlling a simple mix with one dry mix and one wet mix as shown in Figure 6.

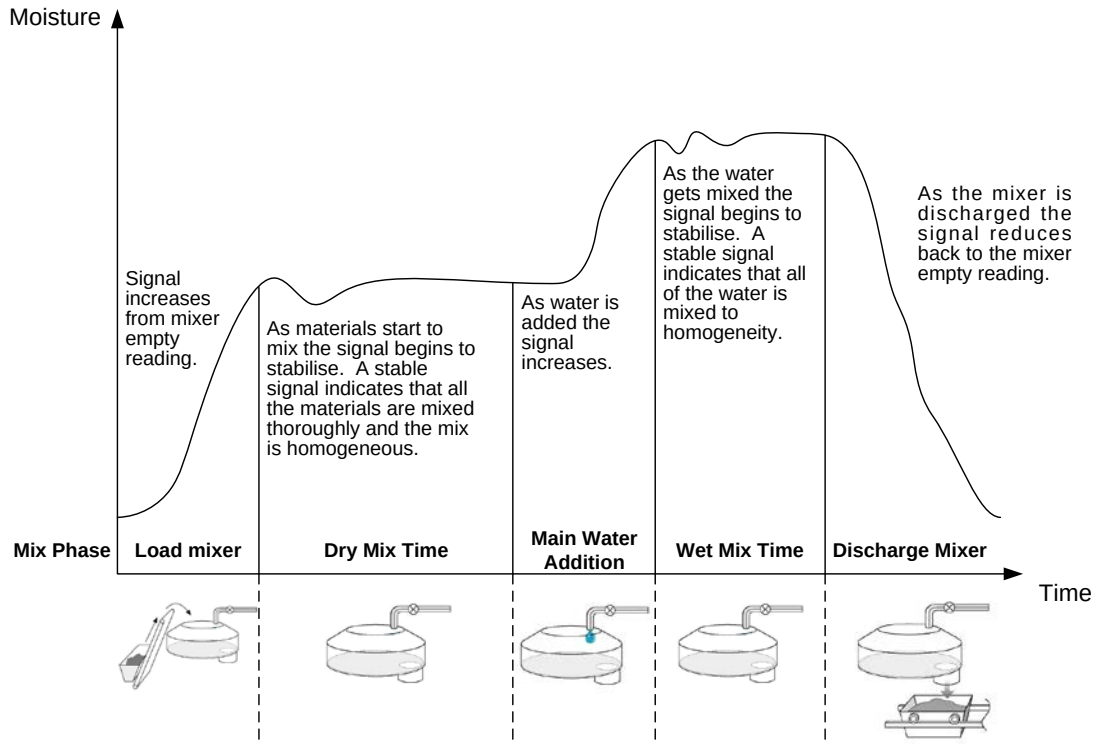


Figure 6: The moisture trace during a mix cycle

Measuring in the mixer during the mixing cycle allows the concrete mix quality to be controlled directly at the point the water is being added and allows a more consistent quality product to be made. For best results it is important to allow the mixer time to mix to homogeneity during both the dry mix and wet mixes, especially during setup and calibration of the system.

Calibration

Calibration of the system can be done in two ways, depending on the result needed. This calibration needs to be performed for each different mix design made as the calibration will be different for different blends of the raw materials, as well as any admixtures and colours used. If the system needs to be calibrated to true moisture, then for each mix design, a dry mix reading and a wet mix reading needs to be made as well as either a sample of the wet mix to test in a laboratory, or the final moisture value calculated from the mix design itself.
If a laboratory test is performed then this needs to be completed very quickly and within a consistent timescale as, once the batch is mixed and water is added, the cement will start hydrating and the moisture content of the concrete will change quickly with time. A similar laboratory test as the aggregate calibration test can be performed but the results may not be completely accurate.

An easier way to calibrate a system is to use the control system to make a batch of concrete which is of the desired quality, and then to use that to 'train' the system on the parameters it needs. In this process, the calibration is performed by making batches of concrete in the mixer adding fixed amounts of water that can be adjusted up and down depending on the batch results. Once a batch of concrete is made that fulfils all of the necessary quality parameters, that batch can be used as a calibration for the system for that mix design.

Calculations

There are two ways to control the actual water being added to the mix. The most important part of the control system is the moisture sensor which must be linear for the system to work reliably. It is also important to use a good quality flow meter for recording the water flow into the mixer and good quality valves for controlling the flow.

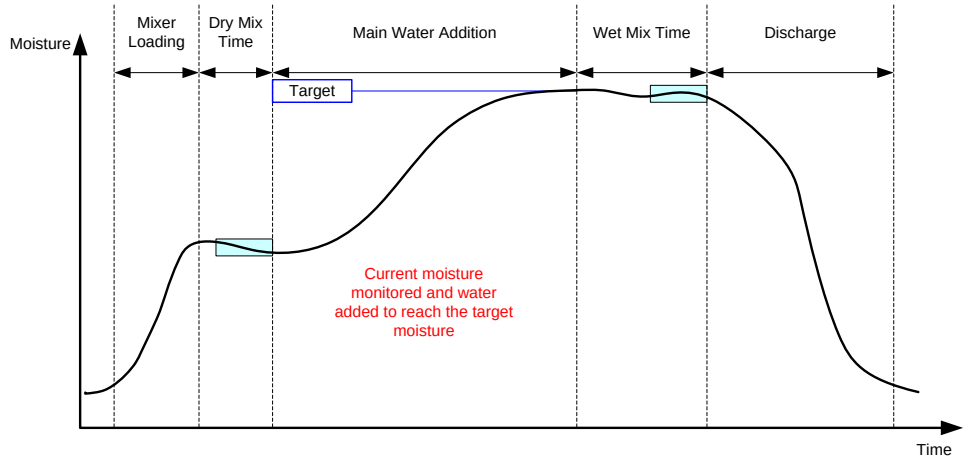


Figure 7: The mix moisture during PID water addition

The first water control method is to select a target value from the sensor and then to control the water with that value as shown in Figure 7. As the sensor is linear, each water step will give the same change in the sensor value. There are a number of ways to control the water addition itself and one of the best methods is using a PID (Proportional, Integral and Derivative) controller. This monitors both the error (the distance from the target value), the rate of change in this error value and the time that this error value has been active.

The PID loop has control parameters which are set for the mixer, valves and mix design. Often the same parameters can be used for different mix designs.

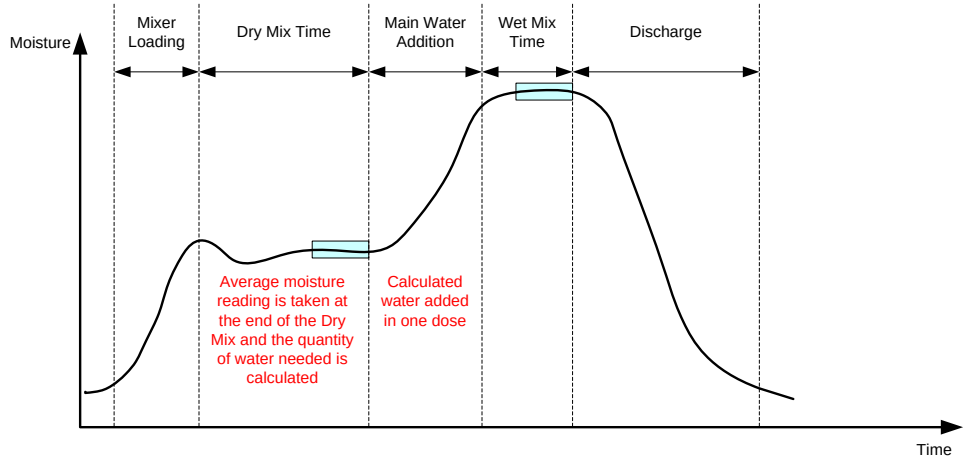


Figure 8: The moisture in the mixer during a calculated mode water addition

The second water control method is to take the selected target value and to make a measurement at the end of the dry mix phase as shown in Figure 8. By using parameters that have been recorded during a calibration mix, it is possible to calculate the exact amount of water needed to achieve the target value and then the water can be added, in one dose,

using an appropriate delivery method (it is not necessarily best to add the water as fast as possible as this can cause problems with certain mixers).
The calculations are simple and based on the fact that the sensor is linear with the moisture level change (not the total water). As long as the dry weight of the batch is known the amount of water can be calculated.

The diagram in Figure 9 shows the dry and wet mix average points that are obtained from the mix. From these values, it can be determined that the gradient of the moisture line is:

$$Grad = \frac{M}{US_{Wet} - US_{Dry}}$$

Where M is the moisture change given by the flow metered volume (V) and the dry weight:

$$M = \frac{V}{W_{Dry}}$$

These should all be calculated in S.I. units (Litres and Kilograms)

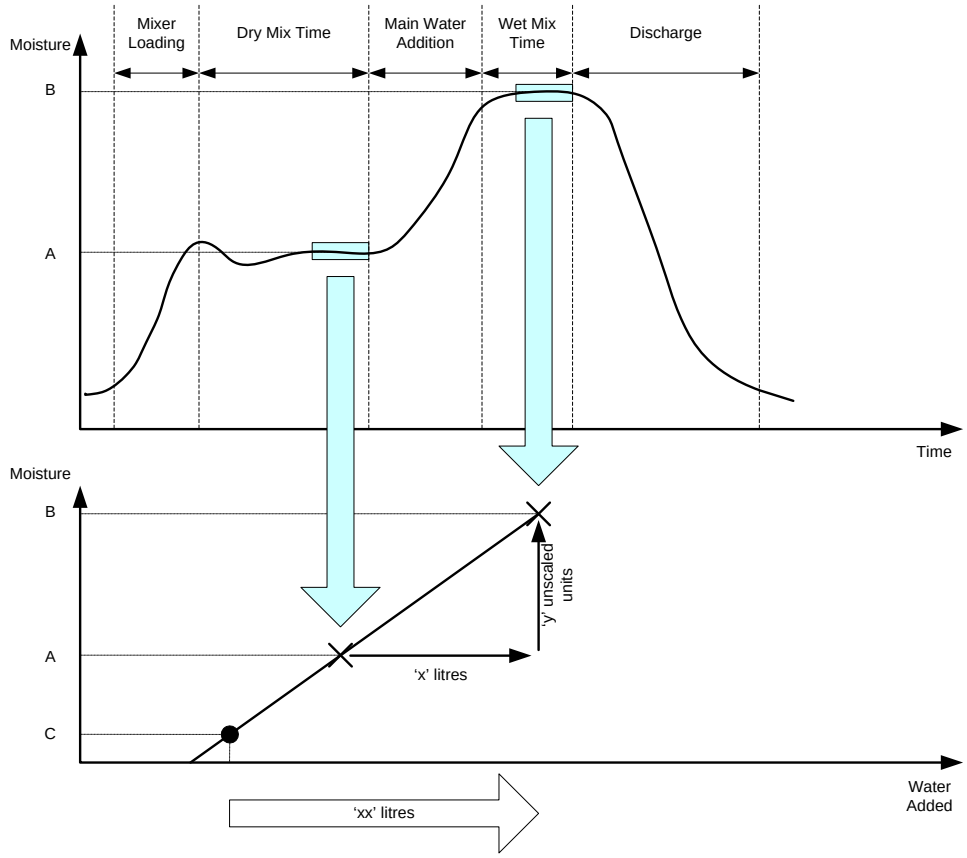


Figure 9: The calculation points from the mix cycle

When a new batch is made and it has a dry mix point as indicated at point 'C' it is possible to calculate the moisture to add given the offset from the previous calculation and using the same target value US_{wet}.

$$M = Grad \cdot (US_{Wet} - US_{Dry})$$

Using the dry weight of the new batch, it is possible to calculate the water to add:

$$V = M \cdot W_{Dry}$$

This volume can then be added in one dose.

4. Conclusion

By utilising moisture control technology, it is possible to reduce the number of wasted batches, control and improve the quality of finished concrete and reduce the amount of cement, admix and colours being used by optimising the quantity added to a batch.
To give an example of the cost savings in cement only, with correctly calibrated moisture control (reducing the moisture error after correction by 2%) it is possible to save 7 kg of cement per m^3 of concrete to still achieve the correct water/cement ratio.

If a plant were making 120m^3 and if you take the cost cement to be USD100 per tonne then total amount of cement saved per year would be 165 tonnes which is USD16,500. It can be seen that installing moisture measurement equipment can quickly return the amount that was invested, typically in less than 3-6 months.