Optical Moisture Measurement in Concrete Aggregates

Taisto Haavasoja
M.D., Ph.D. (Phys.)
Teconer Ltd
Runopolku 1b,
FI - 00420 Helsinki
taisto.haavasoja@teconer.fi

ABSTRACT

We have studied feasibility of using optical means to measure aggregate moisture content. We measured optical response of some commonly used aggregates at around 1.5 µm wavelengths. The results suggest that this wavelength range enables nominal accuracy of about 0.1% in moisture by weight. One of the major benefits in optical technology is a noncontact measurement allowing practically a onetime calibration procedure and a long lifetime of the sensor due to solid state design. On the challenge side there is a need to protect the sensor window from dust and condensing of moisture. These issues have been field tested in concrete plants and a long term accuracy of 0.3% is realistic in practise. We also measured the optical response to a maximum variation in aggregate grading.

Key words: Aggregate, moisture, water content, optical sensor, infra-red spectroscopy.

INTRODUCTION

Coarse aggregates can contain 0-2% surface moisture by weight and fine aggregates even up to 10%. These numbers exclude absorbed water, which ranges typically from 0.5 to 4% according to Ref. [1]. Ultimately, wet aggregates may contain moisture more than is desirable to preserve the water-cementitious material ratio (w/cm) in design limits without overdosing cement. In practise, moisture content of aggregates must be known to fractions of percent to minimise variability in concrete quality and to enable optimal usage of cement. Accurately measured moisture in aggregates allows optimising strength, durability and shrinkage of concrete products. Also knowing the right moisture content prior to mixing permits faster mixing times, when there is no need to add water during mixing.

There are a number of means to arrange measurement of aggregate moisture in concrete plants. The traditional measurement by weighing and drying a sample is satisfactory only in plants, where the aggregates are well mixed by the time of loading to silos so that variation of moisture is minimal between batches. Few plants have this strategy in practise and thus in many plants an automatic measurement is highly recommended.

Currently the most widely used automatic moisture measurement in concrete industry seems to be based on capacitive or microwave sensors and one of the most prominent producers are Franz Ludvig GmbH in Germany and Hydronix Ltd in UK. Capacitive and microwave sensors are installed typically in direct contact with the aggregate either in silos, silo feeders or even over a conveyor belt. The dipole nature of water molecule implies a high dielectric constant of water enabling simple detection in aggregates by coupling to a sensing electromagnetic field. Since the dielectric constant of most aggregates is fairly small compared to water, capacitive sensing produces often a fairly stable result. Nevertheless, direct contact to sample causes mechanical wearing of the sensor requiring occasional recalibration and finally replacement of either the sensor plate or the whole sensor. Few concrete plants have personnel capable to calibrate or maintain the sensor.

Optical detection of material moisture would allow noncontact detection with clear advantages for concrete industry. Optical moisture sensors are based on absorption peaks by water molecules at near infra-red wavelengths. There have been optical moisture sensors available for process industry over tens of years, but they have not been widely used in concrete plants due to their high price compared to microwave sensors. However, development of optoelectronic components thanks to optical communication technology has enabled designing more optimal and economical sensors for measuring surface moisture in aggregates.

In the following chapters we present the basics of optical moisture measurement, a new optical sensor designed for detection of moisture and discuss the challenges of applying the sensor for optical detection of aggregate moisture.

1. OPTICAL MOISTURE MEASUREMENT

Optical moisture sensors employ an active light source transmitting preselected wavelengths bands on the sample. The back reflected light is collected on a detector element for analysis. There are typically at least two wavelength bands in use so that one is on an absorption peak of water molecule and the other is used for a reference signal. The reflected amount of light at absorption wavelength is compared to the reference signal and this information is used to determine moisture content by calibration.

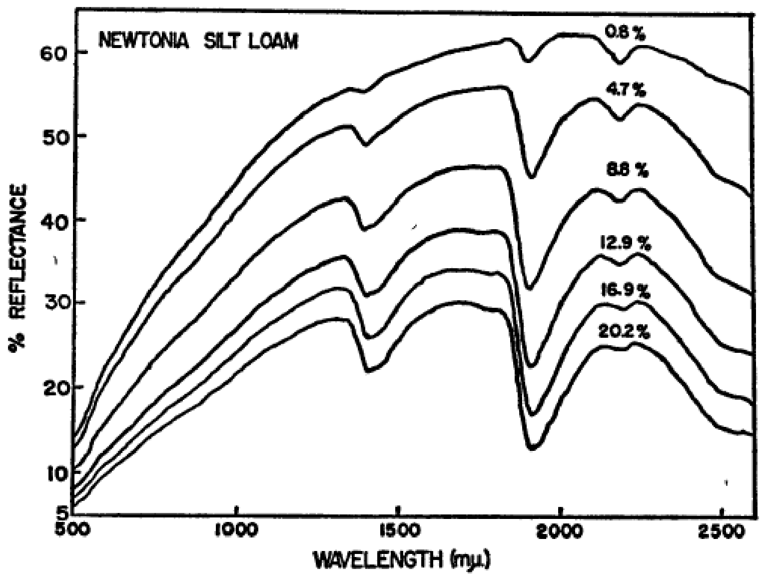

Figure 1 Reflectance of silt loam as a function of wavelength and moisture content in the range 0.8 – 20.2 % according to Bowers and Hanks [2]. There are two clearly observable absorption peaks at about 1.4 and 1.9 µm.

Figure 1 represents reflectance from visible to near infra-red wavelengths as measured by Bowers and Hanks [2] in silt loam. In concrete aggregates the behaviour is generally similar showing decreasing reflectance and increasing absorption peaks with increasing water content. Since water contents in aggregates range only to about 10 % depending on the fineness number, the absorption peak at 1.9 µm is most desirable for water content measurement in aggregates. In practise technological reasons may lead to preference of lower wavelengths.

Traditional optical moisture sensors use broadband emitting hot lamps and a set of filters arranged in a rotating wheel. This technology has the advantage that many wavelengths are available allowing higher detectability with various materials. Currently there are available fairly narrow band near infra-red light sources enabling construction of a simpler and reasonably accurate optical system with clearly less expensive end user price. To our knowledge these traditional optical moisture sensors cost three to four times more than widely used microwave sensors and have not been able to penetrate to this application. Thus we have taken microwave sensors as our reference in this study to compare a new optical technology to existing solutions from a practical point of view.

In literature there is not immensely research available on optical moisture measurement of aggregates with a potentially low cost technology. An example of such a research is by Clemmensen et.al. [3]. They took multispectral photographs of aggregate samples from visible to about 1 micron wavelength and compared various statistical dimension reduction methods for determining moisture of the samples. They notice increase of standard deviation when images are split into sub images indicating inhomogeneity of the samples. The authors recommend appropriate sampling techniques to compensate for the inhomogeneity when applied on process conveyors. To avoid this same problem we had to integrate continuously a moving sample laid freshly on a conveyor.

2. WATER CONTENT MONITOR WCM411

The optical sensor used in this study is called Water Content Monitor WCM411 produced by Teconer Ltd. A photograph of the sensor is shown in Figure 2 and an example of installation over a silo feeder in Figure 3. The sensor is installed typically within 0.5 – 0.8 meters from the sample surface with a dust protection tube as shown in Figure 3. The sensor is supplied with a cable for power (9-30 VDC) and communication (RS-232, 4-20 mA current loop). Repeatability and short time stability of the sensor is about 0.1% by weight. An absolute accuracy of about 0.3% is reachable with a careful calibration and homogeneous sample. This level of accuracy can be maintained for extended periods assuming dust protection of the sensor window is effective. The sensor does not have any moving parts and uses a long lifetime light source allowing an extensive maintenance free service life.

Figure 2 *A photograph of Water Content Monitor WCM411. Diameter of the sensor is 75 mm and length 100 mm. The sensor cable is equipped with a 5 lead connector.*

Figure 3 *An example of a WCM411 installation over a silo feeder belt with a dust protection tube.*

The response of an optical sensor to moisture comes from the sample surface. Some aggregates may be partially transparent and in that case the response may come from some depth beneath the upper surface. Typically this penetration depth is only a few millimetres. Therefore most of the response can be assumed to reflect surface moisture instead of volumetric moisture. In comparison to microwave moisture sensors the main difference is that optical sensors mainly respond to changes in free surface moisture and less to volumetric moisture in contrary to microwave sensors. Thus optical sensors are less sensitive to local variation in particle size distribution.

3. PERFORMANCE

The detection area of WCM411 is fairly small, about 0.05 m by diameter at 1 m distance. Therefore the sample area is often not optically homogeneous, which prevents accurate measurements with static samples. Thus it is better to use a moving sample and calculate an average value to represent a larger amount of the sample. Most accurate calibration of the sensor with a given aggregate can be obtained by starting with about 1-2 % moisture and then adding water, e.g., in steps of 1 % up to about 5 %. A micro mixer is used to mix the sample continuously while adding water after obtaining a stable reading at the given water content. At low moisture content there is a risk of segregation of large aggregate particles on the surface whereas at high moisture content mixing may be ineffective due to the sample being like dough and getting lumpy.

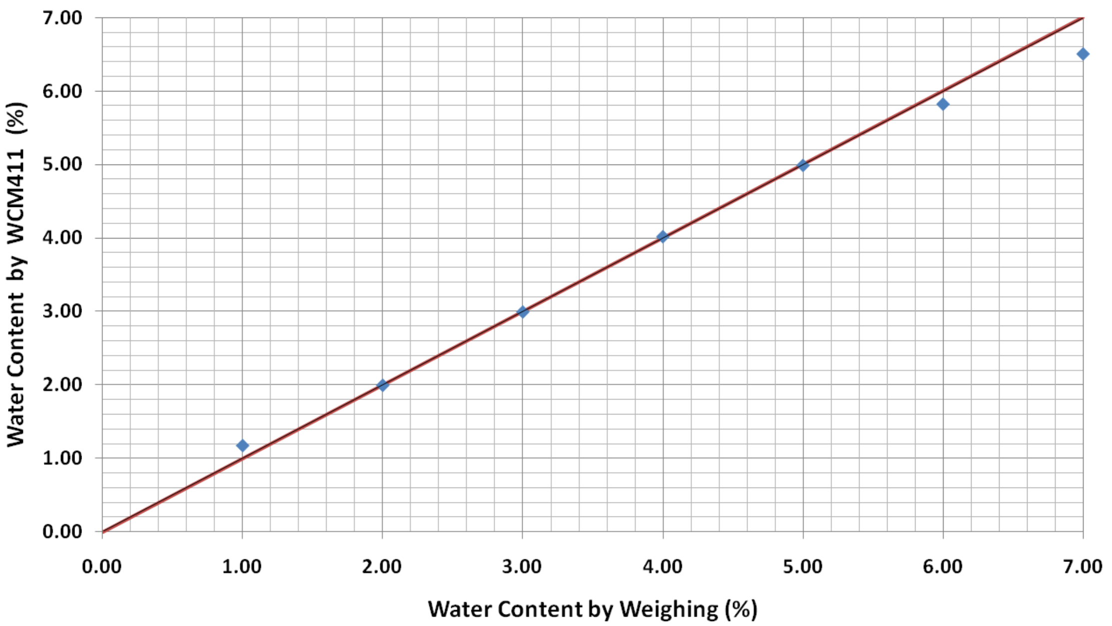

Figure 4 A typical calibration line for a 0-4 mm fine aggregate. The dots represent response to addition of water content in steps of 1%. The line is just a guide to the eye for an ideal response. The apparent deviations at 1%, 6% and 7% come from an incomplete mixing of the micro mixer, which can be revealed by employing another kind of a mixing technique.

Figure 4 shows an example of a calibration with the method described above in a 0-4 mm fine aggregate. As the figure implies an optical sensor can have an extremely high nominal accuracy, fractions of 0.1% at typical moisture contents. However, there are a number of reasons why this level of accuracy is not reachable in practise. Those reasons can be divided to sample dependent and external ones. The former include sample inhomogeneity, e.g. optical properties and local variation in grading. The external reasons are related to stability of the measurement environment and general sampling problems of reference values. A good measure of all these factors together can be obtained by observing a long term scatter of occasional sensor readings and reference values obtained by weighing and drying.

We tested the sensitivity to variation in grading in a 0-8 mm fine aggregate. The grading was changed by adding fine particle fractions up 0.25 mm sieve as much as the norm [4] allows. This corresponded to an increase of about 15 units in fineness number and 8.7% in formal surface area. If the optical measurement interacts only with the top layer of the sample, we would expect the slope of the calibration curve to decrease by the increase of nominal surface area. The change was clearly smaller, from 1.000 to 0.952, corresponding on the average to a reduction of only 0.20 % units in moisture (Figure 5). The result supports the interpretation that the aggregate is to some extent transparent at near infrared wavelengths. Inherent differences in optical properties of finer gradation particles can also cause part of the observed change in calibration.

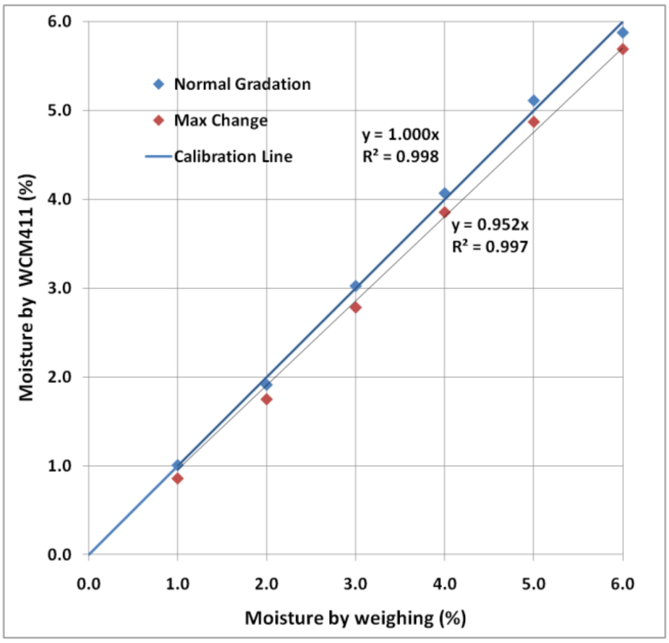

Figure 5 Response of a calibrated sensor (blue dots) to a maximum increase in fine gradation (red dots) corresponding to 15 units in fineness number.

Figure 6 shows the results of a long term test of in a plant environment. The data was collected within four months leaving the optical sensor untouched during the whole test period. The weighed reference values were collected by taking typically three manual samples from a given mixing batch and comparing water loss in drying to corresponding sensor readings.

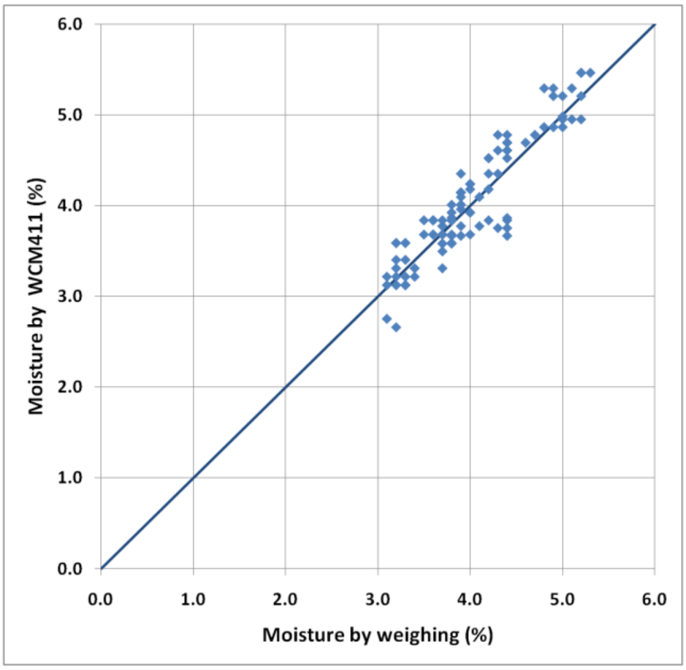

Figure 6 Comparison of sensor readings to a weighed reference value in a long term plant test. The standard deviation of the differences is 0.25% in moisture.

The apparent scatter in the data of Figure 6 has clearly increased as compared to calibration data. However, the standard deviation, 0.25% in moisture, is still fairly low. Surprisingly, the most significant reason for the scatter is not related to the performance of the optical sensor but instead to manual sampling problems of the weighed reference data. For practical reasons the reference samples are on the order of 1 kilogram by mass representing only a tiny fraction of the whole batch and thus being sensitive to local variation. Instead, the sensor readings represent average values of a much larger part of the batch thus representing more likely the average moisture of the batch. Often the three reference samples of a single batch varied almost one percent in moisture from each other whereas some other time the scatter was only a few tenths of percent.

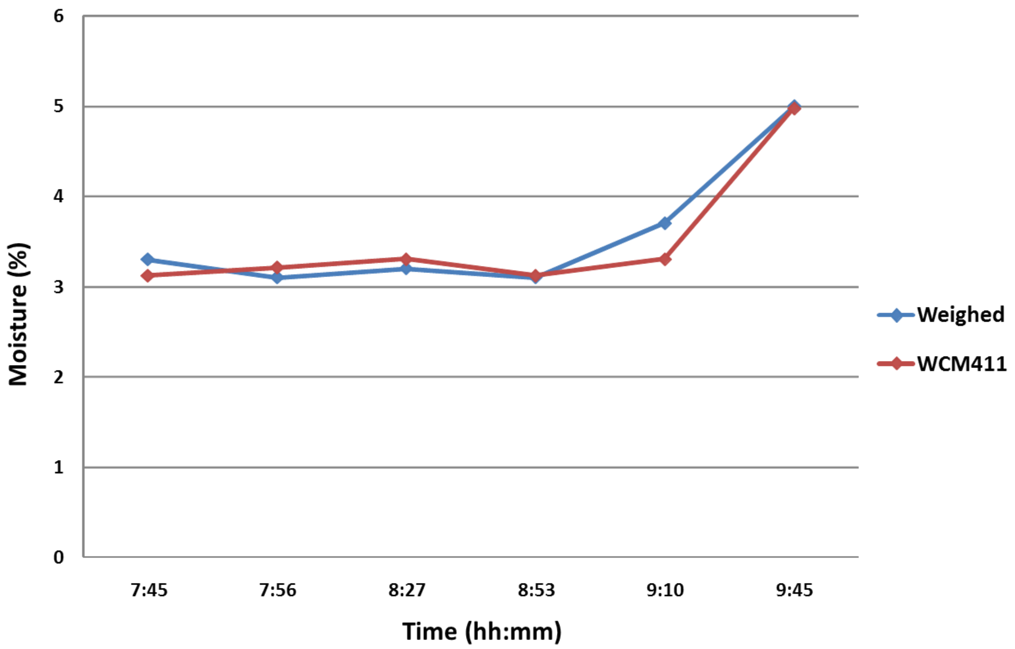

Figure 7 Comparison of sensor readings to a weighed reference value during one morning. The rapid increase in moisture starting at 9:10 levelled off later by the same day.

An example of sudden variation in a silo moisture is shown in Figure 7. Up to about 9:00 the reference values and the sensor readings showed a fairly stable moisture around 3.2%. Suddendly both of the readings started to increase ending to 5% and over. The large and fast increase in silo moisture was probably caused by a heavy raining period a few days earlier. This example shows why it is important to follow aggregate moisture continuously instead of taking only one daily reference sample.

4. CONCLUSION

Optical sensing of moisture in concrete aggregates has been available for some time but it has not been competitive with capacitive and microwave technologies so far. Recent advances in solid state light sources and detectors have enabled designing price competitive optical sensors which can be optimised for a given specific task. We have shown that the performance of an optical moisture sensor competes with microwave technologies. The challenge to keep the optical window clean can be solved with simple arrangements. Noncontact measurement, long lifetime due to solid state design, easy calibration, high accuracy and low need for maintenance will help to deploy optical sensing to measure moisture in concrete or many other industrial aggregates. Most promising applications include moisture in high reflectance materials of mining industry and power production by incineration of chopped wood or peat.

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