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IN-SITU MEASUREMENT OF RELATIVE HUMIDITY AND EXPANSION OF CRACKS IN STRUCTURES DAMAGED BY AAR

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ABSTRACT

This paper demonstrates an in-situ system for measurement of relative humidity and expansion of cracks in structures damaged by alkali aggregate reaction (AAR). The concept of the system is use of inexpensive equipment and that structural owners themselves carry out measurements. Relative humidity is measured by use of wooden sticks mounted in plastic tubes drilled into the concrete. The moisture percent of the wooden stick is manually measured by use of a moisture probe (electrical conductance). Expansion of cracks is measured on 3 triangular arranged rosettes with equal distances on 50 mm. Measurements are manually carried out by a Demec gauge.

Since 1995 the in-situ measurement system, has been in use in a principal road bridge in Trondheim and a dam structure in Southern Norway, both damaged by AAR. The same system has since 1998 been mounted on an important office building damaged by AAR in Oslo. Here, three types of impregnation/coating (two Silanes and one Elastic Acrylic Dispersion) as well as cladding by aluminum plates are assessed according to humidity and expansion. Relative humidity is measured several places on each structure as well as expansion of cracks. The paper gives documentation of the methods and some results of measurements.

The following conclusions can be drawn: humidity measurements by wooden sticks are very stable over time and lies in the interval 80% to 100% relative humidity in structures with AAR. The precision of relative humidity measurements is about +/- 3% when calibration curves valid for only one wooden stick has been used. It can be shown that surfaces exposed to periodically rain obtain higher humidity than leeward surfaces. This are revealed as humidity profiles. For the dam structures no difference in humidity occur between the surface and 40 cm in the concrete. Measurements of cracks show that cracks are "alive" and expand yearly from zero to 0,25mm. Preliminary results of the coating systems suggest that all the systems reduce the relative humidity over time, 3 cm from the outer surface.

Keywords: Concrete structures, durability, in-situ measurements, alkali-aggregate reaction, relative humidity, expansion of cracks

INTRODUCTION

Concrete is a porous material open for transport of liquids and vaporous. The most important constituent for transport in concrete is water. In concrete water occur in the following forms: Chemically bounded to hydration products, Physical adsorbed to inner surfaces and gel pores, Physical absorbed as capillary water in smaller pores and as free water in cracks and "larger" pores. In concrete with Alkali Aggregate Reaction (AAR) water is additional bounded in reaction product (alkali silica gel). Concrete is a hygroscopic material, which means concrete can take up water and liberate water from the surroundings, dependent on the partial pressure in the concrete and the atmosphere. When concrete liberates water to the surroundings it is called desorption and when concrete takes up water from the surroundings it is called absorption. Capillary suction, water pressure and periodically rainwater are important processes for ingress of water to concrete. It is claimed that large massive concrete structures may remain sufficient damp for more than 50 years (Stark 1991).

It is generally accepted that relative humidity is a good measure for assessment of concrete's susceptibility for AAR. When the relative humidity is less than 75-85% it is today accepted that AAR not likely occur in concrete (Nilsson 1981, 1983, Stark 1991). In cases the relative humidity is higher than this limits AAR most likely occur when the concrete mix is reactive and sufficient time have passed since construction period. The literature gives very few examples on humidity measurements in concrete and structures (Stark 1991). This, even humidity is the most important parameter for the durability and repair of damaged structures with AAR.

The damaging effect of AAR is volume increase, expansion and cracking of concrete and movement between concrete members. Expansion measurements of laboratory samples under controlled and accelerated conditions are normal measures for assessment of reactivity of aggregates and concrete mixes. In hardened concrete and real structures the literature only gives few examples on long time expansion caused by AAR. Here expansion results normally are reported as linear expansion by volume or expansion of cracks. It is generally accepted that measurements on real structure give more reliable results than measurements on cores taken from the structure and tested under laboratory conditions (Wood 1990). The present paper gives documentation on long time measurements of relative humidity and expansion of cracks on 3 Norwegian concrete structures damaged by AAR.

HUMIDITY

Measurement of humidity can be done on several ways. Cores drilled out from structures and tested in the laboratory is a destructive method used for measurement of water content and relative humidity. The most used method for measurements of relative humidity is by use of electrical humidity sensors of different types. Normally a hole is drilled in to the concrete and the sensor is put into the hole and isolated from the atmospheric air. When equilibrium with the concrete has been obtained, normally after one to 12 hours, the relative humidity is recorded. Sometimes humidity sensors permanently are mounted into the concrete. Because, electrical humidity sensors are expensive this method is seldom used. Experience in Norway have shown that many of the electrical sensors breaks down within one year in structures located in humid and aggressive environment and also not very successful on a long term basis. Moreover the sensors should be calibrated after two months (Sellevold 1997). The humidity can also be measured indirectly by the electrical resistance of the concrete or by use of e.g. Autoclam and Multiring methods where the electrical conductivity is measured. Generally one can say that humidity measurement often give uncertain and confusing results and are not stable over long time.

Measurement of relative humidity by use of wooden sticks drilled into the concrete has been used in UK and Denmark. In UK, one company has used this method on several structures with AAR (Wood 1985). In Denmark one company has used the method in few structures and for laboratory testing (APM 106 1989). Even the method has been used on several structures in UK and Denmark the reliability, uncertainty and limitation are not known.

Wooden Stick Method – Laboratory

Introduction -- Humidity measurement by electrical humidity probes is a standard method in the paint and wood industry. The electrical conductivity is measured between two "steel needles" with standardized equal distance, which is pressed into the wooden surface. The measurement takes only few seconds to perform. The electrical conductivity correlates well with the water content in the wood (water percent) that is recorded on the apparatus e.g. Protiometer Timber Master (Apneseth & Hay 1992). The temperature has only minor influence on the electrical conductivity in wood, which not are the cases with measurement in concrete (NORDTEST-metoden 1983). As mentioned the method has only been used in a limited amount concrete structure in UK and Denmark and the reliability, uncertainty and limitation are not known. The present paper gives some statistical result from laboratory testing and long time performance of the wooden stick method hereafter called WS-method (Jensen & Haugen 1996, Jensen 1998).

Preparation and calibration of sticks -- The wooden sticks of the type Ramin used in the Norwegian projects have a diameter of 12 mm and are 45 mm long. Before calibration the sticks are impregnated with an Oxide impregnation liquid to prevent the wood to rotten. Correlation between water percent measured by the apparatus and relative humidity has to be done by a calibration curve made under standardized laboratory conditions (20 °C). Salt chambers with different salt solutions in equilibrium with relative humidities of 33%, 54%, 76%, 88%, 95% and 100% (pure water) are prepared. The wooden stick has to be in each salt chamber at least 3 weeks until equilibrium has been established. For each wooden stick is made an adsorption curve and a desorption curve. A calibration curve can be calculated as the average between the adsorption and desorption values. Experience has shown that calibration curves varies between the wooden stick, sometimes significantly. It has to be remembered that the 100% relative humidity value is the fiber solubility point of the wood. Higher water percent can be measured in case the wooden stick is wet (e.g. caused by condensation of water from the air) but the relative humidity is still 100%. Fig.1 shows an example of the adsorption and desorption curves for one wooden stick (no.360). In the figure the 95% confidence limits of 112 wooden sticks are shown with broken lines (calculated as the average of the adsorption values of 112 sticks - 2 standard deviation, respectively the desorption values + 2 standard deviation). It is easy to see that the precision of measurements is improved by use of individual calibration curves rather than by one standardized curve as used in UK and Denmark. Here an "average" adsorption curve normally has been used. The difference between relative humidity from the desorption curve and the adsorption curve can be used as measure for the uncertainty of the measurement. Note also that the inclinations of curves are higher with higher relative humidity which means the uncertainty is reduced with higher relative humilities. Note that when relative humidity > 70% the precision is about +/- 6% for the 95% confidence interval and about +/- 3% by use of individual curves (stick no. 360).

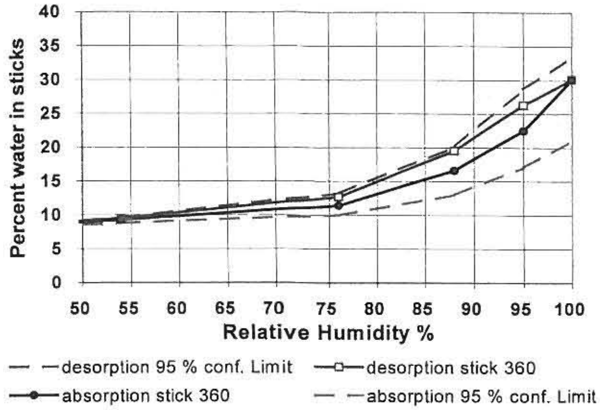

Fig. 1: Calibration curves for wooden stick no.360. In the figure the 95% confidence limits from 112 wooden stick is shown with broken line

Precision -- With aims to assess the precision of the WS - method a correlation test was carried out between wooden sticks and a commercial type electrical humidity probe.

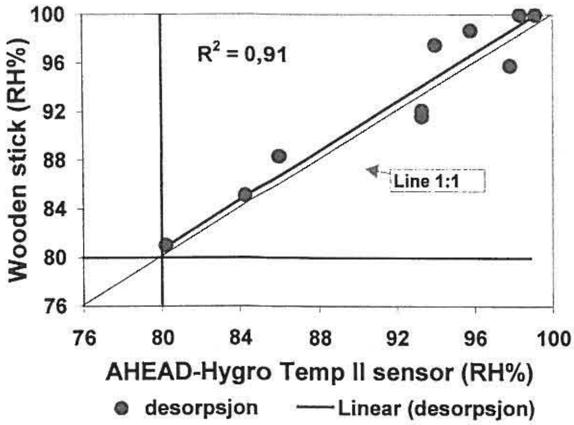

Fig. 2: Correlation between wooden stick with use of the desorption curve and AHEAD hygrotemp II sensors.

Wooden sticks mounted in Elgeseter bridge, Trondheim and frequently measured during a period on 3 years, were sealed in tight plastic bags, and taken in to the laboratory. After laboratory temperature was reached (20 °C) the WS measurements were carried out. The sticks were then put into small tight plastic containers for measurements with the AHEAD hygrotemp II probes. The relative humidity was measured when equilibrium between the wooden stick and air was established. Fig. 2 shows the correlation between the WS – method with use of the desorption curve and AHEAD hygrotemp sensors. Note the acceptable correlation between the two methods. Similar good, but slightly lesser correlation, can be shown by use of adsorption curves.

Wooden Stick Method - Structures

Mounting in structures -- The principle with the WS – method is humidity equilibrium between the wooden stick and the concrete. It is therefore very important that the wooden stick is not in contact with atmospheric air. In the Norwegian projects two wooden sticks (humidity profile) is mounted in a special fabricated plastic tube as shown in fig. 3.

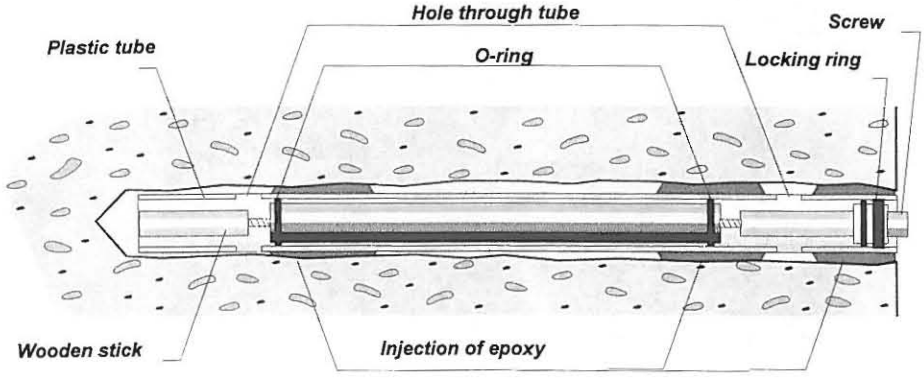

Fig. 3: Plastic tube mounted with 2 wooden sticks. Note that the contact between concrete and plastic tube has been injected with epoxy sealers. Diameter of the tube is 20 mm.

Measurements - Pulling out the wooden sticks and measure the water percent as earlier described does the measurement. It is recommended to make 6 measurements of humidity and one measurement of temperature on each stick within 30 minutes. The relative humidity is measured from the calibration curve or calculated by used of spreadsheet calculations.

Case Stories - Humidity

Elgeseter bridge, Trondheim – The bridge was build in 1949-1951 as a continuous 200 m long reinforced concrete beam bridge supported by 8 rows each with 4 columns with diameter of 80 cm. AAR was diagnosed in 1990 caused by the rock types mylonite, graywacke and argellite. In-situ measurements were established February 1995. In columns several verticals cracks up to 2-mm width can be followed from ground level to the underside of supported beams (10 meters). Some columns also contain map cracking, see fig. 4. Eighth measurement places have been mounted on columns/beam. Humidity by wooden sticks is measured 5 cm and 25 cm from surfaces as well as expansion of cracks, see fig. 9. Humidity profiles through 2 columns 1.2 m over ground level is established, too (western face of columns respectively eastern face), see fig. 6. Measurements of relative humidity have now been carried out for 4 years. Values are very stable with average relative humidity from 99-93 % on western faces, 5 cm and 25 cm inside the concrete and 89-87 % RH on eastern faces 5 cm from the surface.

Fig.4: Map cracking and vertical cracks in columns of Elgeseter bridge. Note that the column (right photo) is wet of rainwater on western face (near the man) and dry on eastern face.

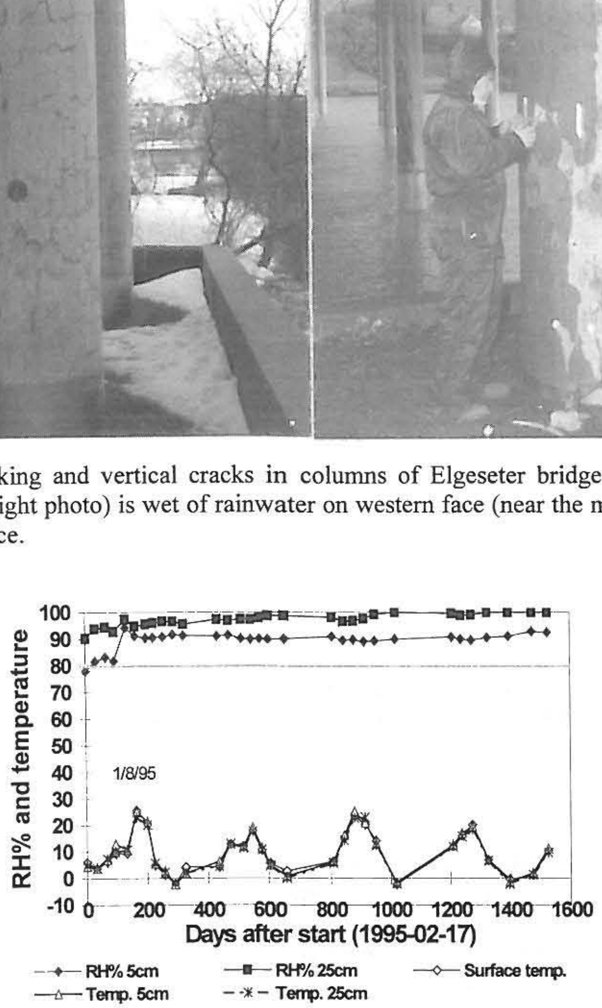

Fig. 5: Relative humidity and temperature (°C) during 4 years.

Figure 5 shows relative humidity and temperature over a 4 years period in location no. 3. Note that relative humidity is very stable over time with a slight tendency of increase 25-cm inside the concrete. In the beginning it takes some time before the wooden sticks are in equilibrium with the concrete. This because the stick was dry when inserted in the concrete. Normally it takes about 1 month before equilibrium is established because sticks now are "wetted" before inserted in the concrete. Note that temperature and yearly

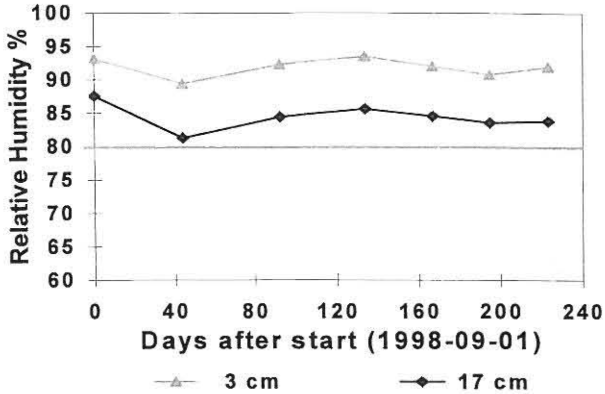

Fig. 7: Relative humidity measured 3 cm and 17 cm from outer surface in location no. 9.

The correlation of all humidity measurements 3-cm respectively 17-cm from outer surface is shown in fig. 8. The distinct difference between coated and non-coated elements is probably accidental.

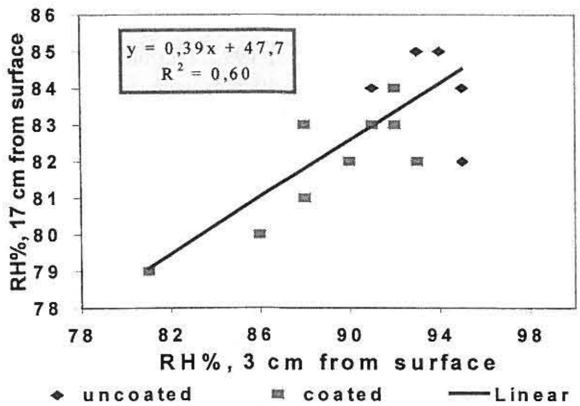

Fig. 8: Correlation of humidity measurements 3-cm respectively 17-cm from outer surface

EXPANSION OF CRACKS

Expansion of cracks is measured by use of 3 triangular arranged rosettes (A, B, C) with an equal distances on 50 mm. Rosettes have been drilled into the surface and hereafter epoxy glued. Measurements along the distance A-B (always along the crack), A-C and C-B are manually measured two times by a strain gauge (Demec gauge). Calculation of expansion (opening of crack) and shear (movement parallel the crack) are carried out by a spread sheet program. All results have been corrected by use of a theoretical temperature coefficient (10^{-5} pr °C). Average expansion results are calculated by regression analysis. Fig. 9 shows a location (with 3 triangular arranged rosettes) for expansion measurements temperature fluctuation do not influence the relative humidity. Fig 6 shows humidity profiles through 2 columns. The profile starts from western faces, which frequently are exposed for rain. Values are average relative humidity over 4 years.

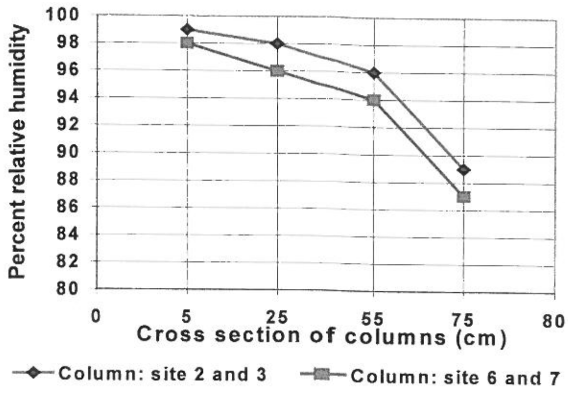

Fig. 6: Humidity profiles through 2 columns of Elgeseter Bridge starting from western faces.

Dam Embretsfoss, Buskerud -- The dam is a massive concrete dam partly hollows (with a gallery) under the gates. The dam was constructed in several periods. AAR was found in the structural parts build around 1947 – 1950 caused by granite and quartzite aggregates. In-situ measurements were established October 1995. Humidity is measured in 3 piers and a wall in the turbine/foundation, 5 cm and 40 cm from the surface. All together 10-measurement places have been established for humidity measurements. Expansions are measured in 7 measurement places. In piers, the relative humidity varies from 97 – 100 % with no distinct variation between 5 cm and 40 cm from the surface. In the turbine foundation wall relative humidity varies from 91 - 94%, 5 cm respectively 40 cm from the inner surface.

Veritas house, Oslo -- The Norwegian Veritas house was built in the early 1970th by prefabricated columns, beams and plates. AAR has been diagnosed caused by impure limestone (metamarl), sandstone and mylonite. In-situ measurements were established September 1998. Relative humidity (20 measurement places) is measured in beams and columns 3 cm from outer surface and in the middle of the elements (17cm). Expansion is measured in 11 measurement places in outer faces of beams and columns. Up to now, results show that the relative humidity is highest in outer surface from 95 – 88 % (one outsider is 81%). In the middle of elements the relative humidity varies from 85 – 79%. All the measurement places show distinct humidity profiles (see figs. 7 and 8). Three types of impregnation/coating (two Silanes and one Elastic Acrylic Dispersion) as well as cladding by aluminum plates are assessed according to humidity and expansion. All the protection systems have been applied the whole outer face of columns/beams. At writing time measurements have only been carried out 220 days and results have not been interpreted. However, preliminary results suggest that all the systems reduce the relative humidity over time, 3 cm from the outer surface.

along a crack, and a neighboring humidity location where the wooden stick has been pulled out of the plastic tube.

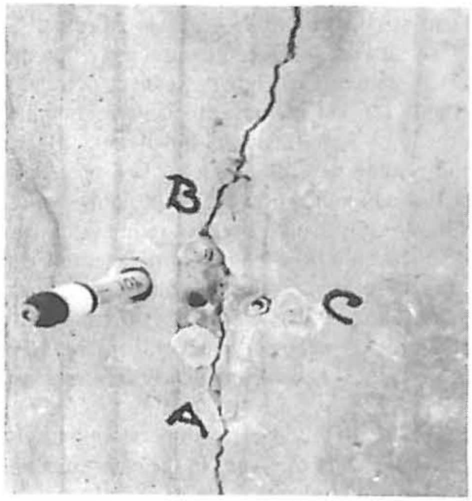

Fig. 9: Location with expansion and humidity measurements, Elgeseter bridge.

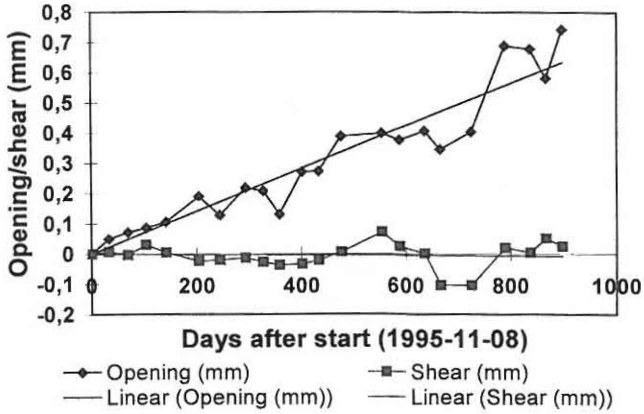

Fig. 10: Opening and shear along a crack in Dam Embretsfoss. The line is calculated from regression analysis.

The in-situ measurement system has now been in use several years in Elgeseter bridge in Trondheim and in Dam Embretsfoss, Southern Norway, both structures damaged by AAR. Up to now, measurement show that cracks are "alive" but with varying expansions. In Elgeseter bridge opening varies from 0.04mm to 0.15 mm yearly and shear from zero to 0.04 mm yearly. In Dam Embretsfoss opening varies from zero to 0.25 mm yearly and shear from zero to 0.07 mm yearly. The in-situ measurement system is now used in other Norwegian structures damaged by AAR.

CONCLUSION

Relative humidity measurements by wooden sticks are very stable over time and lies in the interval 80% to 100% in structures with AAR, as expected. Comparison test between wooden sticks used for 3 years in a bridge structure and a commercial electrical humidity sensor system (AHEAD hygrotemp II) shows excellent correlation. By use of individual calibration curves valid only for one stick the precision in the interval 70% to 95% relative humidity can be better than +/- 3 %. It can be shown that surfaces exposed to periodically rain obtain higher humidity than leeward surfaces. The existences of humidity profiles in bridge columns and beams/columns in an office building have been demonstrated. For piers in the dam structure no significant difference in humidity occur between 5 cm and 40 cm inside the concrete. This even one of the humidity locations is located inside a house on top of a pier (no rainwater). Preliminary results of the coating systems suggest that all the systems reduce the relative humidity over time, 3 cm from the outer surface. However, more measurements and time is necessary to confirm these results. Measurements of cracks show that cracks are "alive" and expand yearly from zero to 0,25mm.

It can be concluded that the in-situ system is operative and gives valuable information about humidity and future expansion of cracks in the structures, information, which can be used for prediction of the remaining service life of the structure and efficiency of repair - coating systems.

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