Impact of Concrete Moisture on Radio Propagation: Fundamentals and Measurements of Concrete Samples

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***Abstract*— Since 1960's concrete based wall panel systems have become more popular especially in multi-storey residential buildings. The main components of concrete are water, cement and aggregates and especially water-to-cement ratio has a significant influence on the pore structure of the concrete and therefore, on its electrical properties. This paper presents a study where the effect of moisture on the RF attenuation of the outermost concrete sandwich element is examined based on material samples. The frequency range used in the measurements was 7 GHz to 13 GHz, but the results are expandable for other frequencies based on the stable permittivity value. In particular, at higher frequencies, the attenuation of concrete layer increases rapidly and already at lower frequencies of 5th Generation (5G) networks, the wetting of the outermost layer of the concrete element can cause an 6-12 dB additional signal attenuation.**

***Keywords*— Radiowave propagation, penetration loss, outdoor-to-indoor propagation, RF measurements.**

I. Introduction

In this paper, the effect of moisture on the RF attenuation of sandwich elements is investigated at frequencies of the 5G cellular network. The motivation of the study has been observation from the earlier field measurements that the RF attenuation of the walls has varied remarkably between different measurements, even if the measured building wall has been the same all the time. The measurement arrangements have also been identical, only moisture of the outer concrete layer has been changed. Inspired on this discovery, the effect of moisture for RF-attenuation has been studied by varying the moisture of the concrete specimen in a controlled manner and by measuring the RF-attenuation during the drying process of samples. The most interesting frequencies for research are the first frequencies of upcoming 5G networks, such as 3.5 - 3.9 GHz frequency band.

The rest of this paper has been organized as follows. Section II covers the most used wall facade structures and materials in residential buildings, especially in Northern European countries like Finland. This section also describes concrete as an external wall assembly material, its properties and internal pore structure. The section as well briefly discusses the concrete wetting mechanisms. Section III describes the parameters that can be used to assess the electrical behavior of a measured material and section IV describes the measurement setup and method used in this study. Section V illustrates the preparation of the measurement samples used in the measurements and section VI presents the results. The conclusions are finally presented in the last section VII.

II. Overview of Concrete Facades

During 1960s and 1970s concrete-based construction increased vastly across Europe. The reason behind this was the high housing demand due the changes in social structure in Europe and migration from the rural to urban areas in European countries. Concrete became popular construction material since multi-storey apartment buildings made of using concrete panel system proved to be efficient solution for the increasing housing demands [1]. The RF-attenuation of concrete wall structures are particularly important for mobile network designers, because the difference of outdoor-indoor signal level is mainly determined by propagation losses through building's walls.

A. The Most Typical Concrete Facade Structure

Typical concrete wall structure in multi-storey residential buildings is a prefabricated concrete panel system consisting of two concrete layers with a thermal insulation located between the layers. Thermal insulation used in these structures is most typically mineral wool but also other materials, based on polyurethane compounds are used. Thermal conductivity and other properties of these materials vary which results in different thermal insulation thicknesses depending on energy efficiency requirements. Therefore, the thickness of the thermal insulation layer depends on the insulation material as well as on the building regulations in force at the time of design and construction [1]. Typical thickness of an inner concrete layer is around 150 mm for load-bearing walls and around 80 mm for non-load bearing walls. The thickness of the outer layer varies typically between 50 mm and 80 mm [1,2,3].

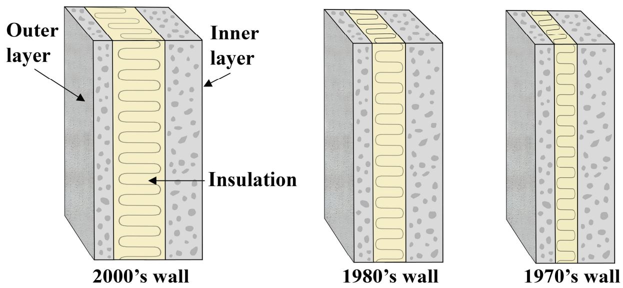

Fig. 1 Typical structures of concrete sandwich elements

B. Material Properties of the Concrete

Because the moisture has a remarkable impact for RF-attenuation of any material, the brief description to the internal structure of concrete is needed; why the concrete is so sensitive for humidity and where the moisture exists. Concrete is composite material consisting of three basic components: water (20%), cement (10%) and aggregates (70%) [4,5]. Hardened concrete forms a porous, stone-like material, which has high compressive strength. In commercial concrete, separate additives are often used for example in order to either accelerate (accelerants) or slow down (retarders) the hardening process of fresh concrete or to increase the workability of the concrete (plasticizers). Another chemical admixture often used in concrete mainly in cold climate areas, are air-entering agents, which increases the frost-resistance of the hardened concrete by forming pores inside the concrete, where the freezing water can expand. [1,4,5]

It should be noted, that the exact proportions of the raw material vary depending on the usage purpose of the concrete. The quantity of the admixtures of the concrete is no more than 5 per cent by mass of the cement [4]. Among the basic components of the concrete, the cement is substantially more expensive to produce than the other components [5]. Therefore, the proportion of the cement has been reduced or partially replaced by other materials with hydraulic properties, which often are by-products of other industries. Fly ash and blast furnace slag are examples of the materials, which are used as a cement replacement in the concrete mix [4].

The most widely used cement is called Portland cement and it is made primarily from limestone or chalk and from alumina and silica. Raw materials of the cement are grinded and burned in a high temperature, forming sintered and partially fused product called clinker. The materials of the Portland cement can be found widely around the world, which is also a reason for its popularity. [4] The hardening of the concrete occurs through to the hydration reaction of the cement. The hydration is a continuous process, and precipitation of solid phases lowers the saturation of the pore solution allowing the dissolution of the cement minerals to continue. Hydration reaction may proceed several weeks. [5]

C. Pore Structure of Concrete and Water-to-Cement Ratio

The volume of the hydration products is smaller than the combined volume of the cement minerals and water combined. Capillary pores represent the part of the gross volume of the concrete, which has not been filled by the hydration products. In general, the size of these pores varies between 10 µm and 50 nm. Water-to-cement ratio (w/c-ratio) is an important factor affecting the properties of the concrete. Especially the porosity of the concrete is highly dependent on the w/c-ratio of the fresh concrete [4.] The 0.4 w/c-ratio is needed for a full hydration, however in commercial concrete the w/c-ratio is typically around 0.6 [5]. Higher w/c-ratio than 0.4 always cause some volume of capillary pores to exist even after the hydration process has been completed [4]. With w/c ratio 0.7 or higher the capillaries inside the concrete remain continuous even after full hydration. Continuous capillaries increase the permeability of the concrete and are regarded to increase concrete's vulnerability to freeze-thaw cycles [4].

The pore structure of concrete has been subject of numerous studies. Typically, these studies focus on the influence of the pore structure to the durability of the concrete. From RF attenuation perspective, the pore structure of the concrete is related to the drying and wetting of the wall structure as well as to the moisture transfer inside the concrete. The moisture content of the concrete have relation to higher RF attenuation levels, especially at high 5G frequencies.

D. Moisture in Concrete

Water is a basic component of concrete and as discussed earlier concrete contains water due to its making process. Generally, water held in the concrete can be classified into three phases. Some of the water becomes a part of hydration result, one part absorbed on the surfaces of the calcium silicate hydrate (C-S-H) –gel and free water is held in capillaries of the cement paste. [4,6,7]

Concrete is hygroscopic material, which means that it has an ability, due to its porous nature, to store moisture from or release moisture into the surrounding air. Pores of the concrete are filled with humid air or in a case of new concrete with free liquid water [8]. The moisture inside the concrete can transfer in a liquid form through capillary suction or in a form water vapor through a diffusion or in the combination of the two [9]. External moisture loads in cases of concrete wall structures are mainly precipitation, especially wind-driven rain (WDR) and the moisture of the outdoor and the indoor air. In some cases, water leakage through certain defect in the joints of the wall panels, for example, is a possible source of moisture [8, 9].

III. PERMITTIVITY OF MEASURED MATERIALS

The effect of the moisture of the materials or structures to the electrical behavior can be investigated by various methods. One of the most useful methods is to determine the permittivity and permeability of the material in different frequency ranges when the material sample is wet and dry. When the examined samples are building materials, in this case mostly concrete samples, attention is paid especially to the determination of the permittivity value, because for the permeability the value 1.0 can be used for non-magnetic materials. [10] In this study, the value of permittivity was determined by the Nicolson-Ross-Weir method (NRW), which is a commonly used procedure in materials research.

The method is based on the measurement of scattering parameters of a material sample and, on the basis of these, there is a rather straightforward calculation of permittivity. However, the method has some limitations for the sample. Sample is assumed to be homogeneous and isotropic. [11] Generally, permittivity, ε, is the most important electrical property of a non-conductive material, and it is divided into real and imaginary parts in the following way:

$$\varepsilon = \varepsilon_r \varepsilon_0 = (\varepsilon_r' - j\varepsilon_r'')\varepsilon_0, \quad (1)$$

where ε_r is the relative permittivity of the material and ε_0 represents the permittivity of the vacuum. Within the parentheses of the equation, the material's permittivity is further divided into two separate factors, of which ε_r' represents the dielectric constant's real part of the permittivity and $j\varepsilon_r''$ is the imaginary part of the permittivity. [12]

When examining samples using the NRW method, the needed S-parameters are typically measured using a network analyzer. The required S-parameters are S_{11}, which is the reflection coefficient of the material, and S_{21}, describing the transmission coefficient. From these coefficients the actual material surface reflection coefficient Γ can be solved deploying the auxiliary variable X.

$$X = \frac{S^2{}_{11} + S^2{}_{21} + 1}{2S_{11}} \quad (2)$$

$$\Gamma = X \pm \sqrt{X^2 - 1} \quad (3)$$

The reflection factor Γ can be used to find a value for the propagation factor T following way

$$T = \frac{S_{11} + S_{21} - \Gamma}{1 - (S_{11} + S_{21})\Gamma}. \quad (4)$$

The permittivity of the material can be defined by using reflection coefficients and wavenumber values

$$\varepsilon_r = \left(\frac{1-\Gamma}{1+\Gamma}\right)\frac{k}{k_0}, \quad (5)$$

where k_0 is free space wavenumber (2π/λ) and

$$k = \frac{j}{d}(\ln(T) + n2\pi, \text{n} = 0, \pm 1, \pm 2, \pm 3 \ldots, \quad (6)$$

where the d is the electrical thickness of the material sample. The loss of a material sample is often represented by the loss tangent δ by following way:

$$\tan\delta = \frac{\varepsilon_r''}{\varepsilon_r'}. \quad (7)$$

IV. MEASUREMENT SET-UP

There exists several different ways to determine electrical properties of material sample. In this study, the free space method was used with 7-13 GHz frequency range.

The resonator-based method is perhaps the most common way to determine the electrical properties of the material being studied. From the examined material, a certain size specimen is cut and located as a part of the resonator structure. Based on changes in the resonance, the electromagnetic properties of the sample can be calculated.

Also, another commonly used method, is a Reflection-Transmission (RT) method in which S-parameters of a sample is measured. In this method, the reflected fields (S_{11}) and the fields passed through the samples (S_{21}) can be used to compute the electrical properties of the studied material. In the examination of flat or plate-like samples, the RT method is useful and often a sample piece is placed as part of a waveguide structure. In both methods described above, the challenge is the very precise shape and size of the samples. Even a small manufacturing defect in the specimen causes air gaps and these air gaps significantly reduce the accuracy of the measurement results. The very strict shape and size requirements of the specimens can be relieved by using the free space measurement with the two antennas, which were also used in this study (Fig 2). However, attention must be paid to the antennas, because the electric and magnetic fields varies on the sample surface, when using conventional antennas. Therefore, it is necessary to use focusing antennas, which concentrate radiation to a small area. Another important reason for the use of specific antennas is to reduce the effect of diffraction from the edges of the material sample.

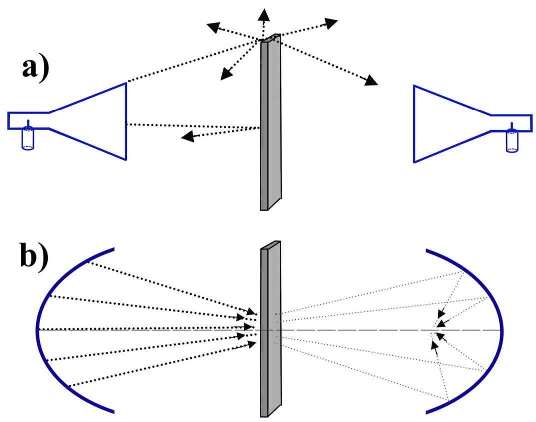

Figure 2. Differences in the free space measurement using conventional (a) and focusing antennas (b).

The measuring arrangement based on using focusing antennas has elliptical radiators mounted on both sides of the sample to be measured, which accurately centralize electromagnetic radiation at one point. The examined sample is located in this focus point.

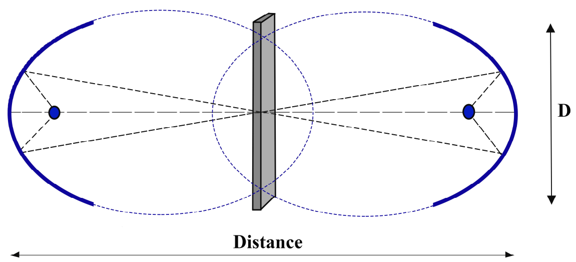

Figure 3. The basic operation of elliptical reflector antennas.

In the measurements, the used circuit analyzer was calibrated by the True-Reflection-Line (TRL) method. There is no sample in the sample holder to measure the true value, and in the Line measurement the sample holder is still empty, but the distance of the reflector is changed to approximately λ/4. The Reflection value is calibrated by placing a highly reflective metal plate in the sample holder. In addition to accurate calibration, it is often necessary to adjust the time domain gating to eliminate the effect of multiple reflections.

Figure 4 shows the measurement arrangements. Reflectors of approximately 400 mm diameter are placed on both sides of the sample holder, and they are fed with waveguide feeds. The focus area diameter at the center of the sample holder is roughly one wavelength.

Figure 4. The free space measurement setup of this study

V. SAMPLES USED IN MEASUREMENTS

The concrete samples used in the measurement were first cast into a rectangular mold from which the pieces were cut after one-month hardening of the concrete. The width and height of measured concrete samples were approximately 150 x 150 mm pieces and due to the measurement method requirements, the thickness of the samples was only 15 mm.

All samples were roughly 4 months old during the measurements, and because they were thin, the pieces could be assumed to be completely dry. One set of the samples were dried for three days in an oven at 105 ° C. This oven drying was intended to ensure that the water content of the samples was as low as possible. The oven drying was done about 2 months after sample fabrication, and thereafter the humidity in the room air slightly changed the weight of the samples.

The actual measurements were started with completely dry samples, measuring the weights and S-parameters of all samples. Then the specimens were immersed in water where the materials were for two days. After lifting up from the water, the specimens were weighed and measured. The following weight measurements of the samples were made 24, 48, 72 and 170 hours after the first measurement. RF-measurements were made only 24 and 70 hours after the first measurement at frequency range 7-13 GHz, in which the ε_r values were calculated from the S-parameters.

VI. MEASUREMENT RESULTS

The results are divided into three groups, the first one being the drying rate of the samples after wetting. The second group shows ε_r values calculated on the basis of S-parameters, and the last group evaluates how moisture affects the signal attenuation of the outermost concrete layer of real sandwich wall element. The data behind following figures has been collected to Table II.

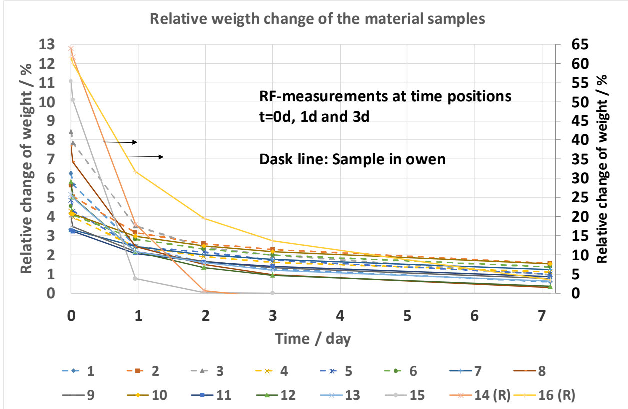

Figure 5. Relative weight change of the material samples

Figures 5 and 6 show the measured drying of concrete samples, which is based on relative changes in the sample weight. In figure 5 it should be noted that for samples 14 (Lightweight concrete) and 16 (Wood), the right-hand axis of the image should be used. Their relative weight change is considerably greater compared to concrete samples. They act as a reference in the figure reminding that the moisture varying of other wall materials is also very large.

In Figure 6, only concrete samples have been taken into consideration and only the change in humidity during the first day has been studied. It can be seen that the weight of the samples dried in the furnace change relatively more than the weight of samples stored in the normal room conditions.

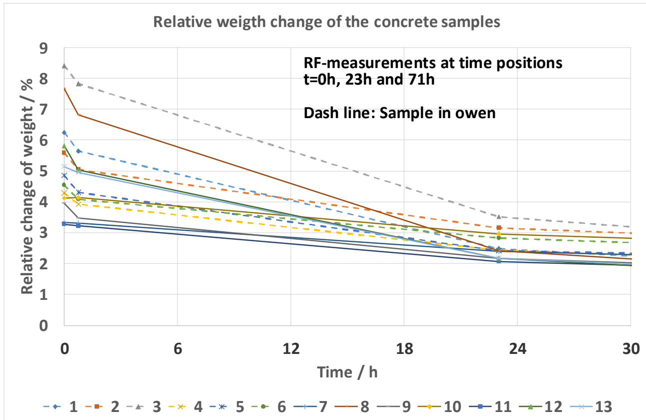

Figure 6. Relative weight change of the material samples, first day

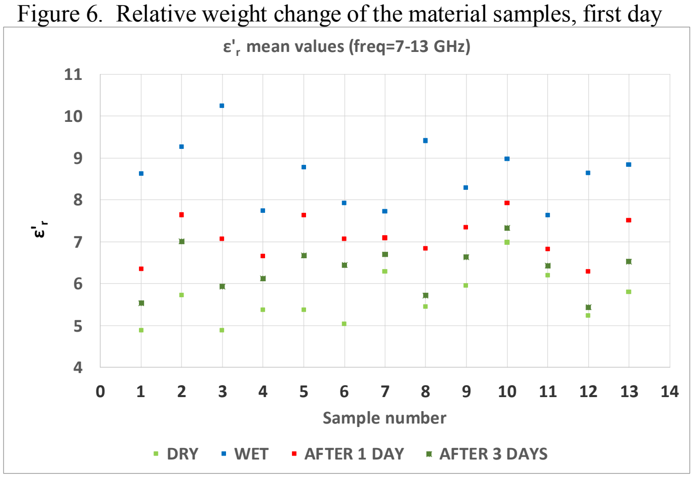

Figure 7. ε_r' –values of the measured samples.

Table II Properties of the measured samples

Sample	*Material*	*W/c-ratio*	*Type*	*d [mm]*	*ε'r Dry*	*ε'r Wet*	*ε'r Day 1*	*ε'r Day 3*	*Tanδ Dry*	*Tanδ Wet*	*Tanδ Day1*	*Tanδ Day3*
1	Concrete[1]	0.7	S100B	13.7	4.89	8.62	6.35	5.53	0.045	0.20	0.11	0.067
2	Concrete[1]	0.7	SB45B	10.5	5.72	9.27	7.64	7.01	0.038	0.16	0.11	0.091
3	Concrete[1]	1.0		15.6	4.89	10.25	7.07	5.94	0.037	0.26	0.13	0.089
4	Concrete[1]	0.4		14.7	5.38	7.74	6.67	6.12	0.035	0.14	0.09	0.069
5	Concrete[1]	Old		16.7	5.37	8.79	7.63	6.68	0.043	0.22	0.13	0.091
6	Concrete[1]	Stand.		13.2	5.04	7.92	7.06	6.45	0.034	0.18	0.12	0.087
7	Concrete	Stand.		16.8	6.29	7.73	7.09	6.70	0.084	0.16	0.13	0.10
8	Concrete	1.0		14.8	5.45	9.42	6.84	5.73	0.061	0.17	0.10	0.063
9	Concrete	Old		14.3	5.95	8.29	7.35	6.64	0.061	0.15	0.11	0.084
10	Concrete	0.7	SB45B	14.4	6.99	8.99	7.92	7.34	0.094	0.16	0.13	0.10
11	Concrete	0.4		16.0	6.19	7.63	6.83	6.43	0.074	0.14	0.10	0.082
12	Concrete	0.7	S100B	13.2	5.24	8.65	6.29	5.44	0.063	0.20	0.11	0.074
13	Concrete	Old		15.3	5.80	8.84	7.51	6.53	0.060	0.23	0.16	0.10
14	Lightweight concrete			13.9	2.15	16.05	4.86	2.14	0.061	0.42	0.24	0.051
15	Brick			16.6	4.22	11.01	4.73	4.21	0.0070	0.24	0.04	0.0050
16	Wood			23.4	2.21	4	3.3	3.11	0.109	0.88	0.57	0.38

Because the measured $\varepsilon_r{}'$ and tanδ values were quite stable over the frequency band, the average $\varepsilon_r{}'$ and tanδ values were calculated and shown in Table II. In the table II, the pieces that have been in the oven are marked with 'concrete[1]'. 'Day1' and 'Day3' values correspond to the measurements performed after 24 and 72 hours after the pieces had been removed from the water. In the table, column 'd[mm]' indicates the thickness of the sample. For a few samples, the w/c-ratio column is labeled with 'Stand', which refers to a commercial concrete type taken from a mixing truck and 'Old' is representing a sample taken from a concrete element about 30 years old.

Figures 7 and 8 show different $\varepsilon_r{}'$ and tanδ values for the measured samples. Generally, both values increase strongly when material moisture increases, but the effect of moisture seems to be greater for those samples that have been in the oven for three days. Likewise, the w/c-ratio appears to be of considerable importance, because the values measured on different days have the highest deviation for those with the highest w/c-ratio. The smallest effect on moisture appears to be when the w/c-ratio is low and the drying of the oven has not affected the progress of the hydration (sample 11).

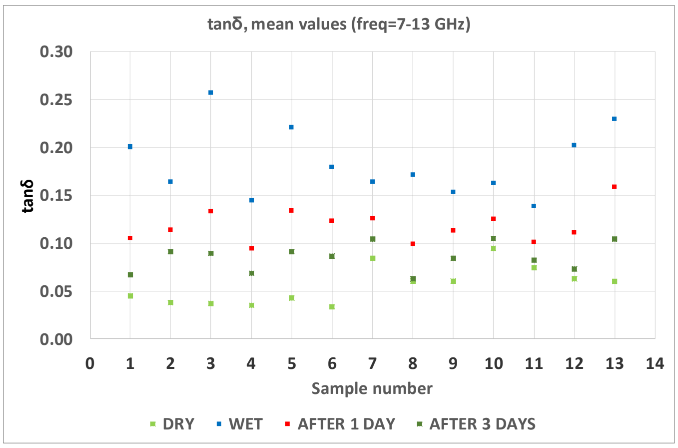

Figure 8. The tanδ –values of the measured samples.

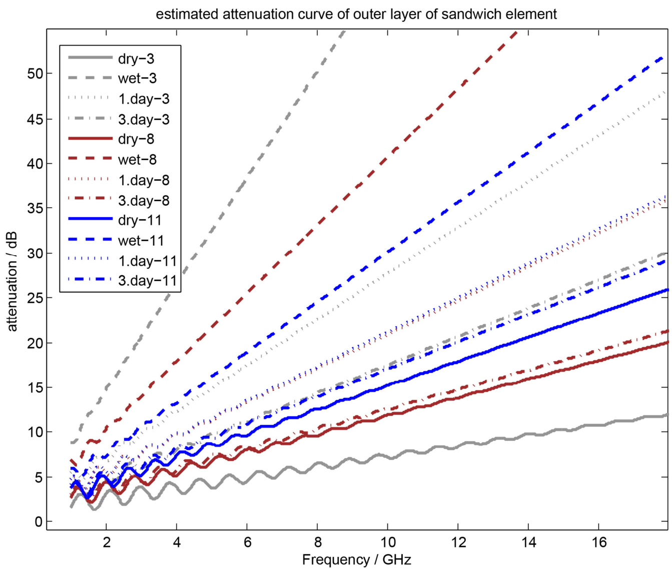

Figure 9. Estimated attenuations of outer layer of sandwich element, when moisture of the concrete changes.

Figure 9 shows the attenuation of the sandwich element outer concrete layer based on the measured S-parameters and the electrical parameters calculated from them. It can be seen from the picture that RF-attenuation is decisively influenced by the moisture of the structure, especially at the incoming 5G frequencies. In the figure, only three samples of all measured specimens are included, and the attenuations of which are shown as dry, wholly wet and in two different drying stages. Samples were selected on the basis of relative weight change, whereby samples 8 and 11 represent situations where the weight has risen the most and the least when the material has been immersed in water. For comparison, sample three, which has been dried in the oven for three days, is included. The most apparent difference between samples 8 and 11 is the w/c-ratio used in the manufacture of concrete, which is the most significant single explanatory for the variation in RF attenuation. An interesting detail in the Figure 9. is that, although the curves of the sample 11 go closest to each other, they all give higher attenuation values than the curves of sample 8. Based on these results, the smaller is the w/c-ratio in the concrete, the denser is the internal structure of the material. Resulting from the increased density there is a higher primary attenuation than with the higher w/c-ratio concrete. On the other hand, with a higher w/c-ratio, the humidity affects the overall attenuation more.

VII. CONCLUSION

Generally, the moisture of the concrete wall substantially affects the attenuation of the whole exterior wall of the building. At its lowest, it seems to cause an additional attenuation of 6 dB at 4 GHz, and with higher w/c-ratio, additional attenuation at the above 4 GHz frequency the attenuation can be even 12 dB.

Based on the results the pore structure of the concrete has an impact on the RF attenuation. High w/c-ratio results in a more porous concrete with a lower attenuation when dry. Porous concrete also stores more water during the submerging and due to this the attenuation rises significantly. The lower w/c-ratio causes the concrete to have a denser pore structure and therefore the attenuation of a dry sample is higher compared to concrete that is more porous. However, with the concrete having a lower w/c-ratio the influence of moisture on the attenuation increase is significantly smaller due to the lesser pore volume. The samples, which were dried before the measuring, have overall, a lower attenuation before the submerging compared to the other concrete samples. This is due the fact that the hydration has been able to progress further inside the samples, which were not dried, reducing the pore volume.

The samples in this study were stored in indoor conditions and were not exposed to external moisture excluding the submerging during the measuring. The relative humidity in which the samples were stored, differ significantly from the outdoor environment. In addition, the samples in this study do not resemble the typical sandwich wall panel in terms of dimensions. The nominal thickness of the exterior concrete layer of the sandwich element is around 80 mm while the thickness of the concrete samples varied between 10 mm and 17 mm. After the submerging, the samples were fully saturated.

The wind-driven rain (WDR) is considered the largest source of moisture for concrete walls in humid climates [8,9,13,14]. WDR is defined as rain with a horizontal velocity component given by wind [13,14]. In North-Western and North-Eastern Europe the WDR comes mainly from South-West direction [14,15]. In addition, the upper parts of walls and facades receive more rainfall than lower and central parts [15]. It should also be noted that generally the amount of rainfall varies depending on the time of the year and each year itself is different [14,15]. This is noteworthy not only because of the moisture load of the WDR, but because of the drying conditions of the concrete since the concrete facades dry mainly from the exterior surface. In general, during long periods of rain combined with high relative humidity of the ambient air and low solar radiation, the moisture content of the concrete exterior wall is expected to be at the highest. This is supported by the findings regarding the corrosion rate of steel rebars inside of the carbonated concrete. The corrosion rate is closely related to moisture and is at the highest during autumn-winter [16].

The moisture content of the external layer of sandwich panel in use depends heavily on the outdoor conditions and therefore direct comparison between the samples of this study and concrete sandwich wall structures cannot be made directly. However, the results of this study indicates that the moisture of concrete has a substantial impact on the RF attenuation.

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