

Determining the Pore Size Distribution in Synthetic and Building Materials Using 1D NMR

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Abstract

NMR is gaining increasing interest in civil engineering for applications regarding microstructure characterization as e.g., to determine pore sizes or to monitor moisture transport in porous materials. This study reveals the capability of NMR as a tool for pore size characterization. Therefore, we measured floor screed and synthetic materials at partial and full saturation. For most examined materials, the pore size distribution was successfully determined using either a reference or a calibration method. Since diffusion effects were observed for some samples in single-sided NMR measurements, further tests employing an NMR core analyzer were carried out in a homogeneous magnetic field. The finally obtained surface relaxivity of floor screed (50 $\mu\text{m/s}$) resulted to be much higher than suggested by literature.

Keywords

NMR relaxometry; pore size distribution; building materials; floor screed; porous materials; surface relaxivity

1. Introduction

Due to the high damage potential of moisture, its detection is an important task in civil engineering. Penetrating water in building materials is one main cause for damage processes as e.g., corrosion and mold. To detect moisture and to estimate the extents of possible moisture damages at buildings and construction sites, several non-destructive monitoring methods and handheld devices can be applied. Main aspects of investigations are the resolution of moisture gradients as well as changes in the pore system. However, to better understand and prevent further material degradations caused by penetrating moisture, more expertise about the pore systems and the relevant transport mechanism (e.g., diffusion) in porous systems of building materials is still needed.



The method of nuclear magnetic resonance (NMR), especially proton NMR relaxometry, is suitable for the detection of moisture because it is highly sensitive to hydrogen protons. In detail, NMR measures different relaxation rates of hydrogen protons in dependence of their physical and chemical bonding. Furthermore, these relaxation rates are also influenced by the proton's environment and, therefore, the signal also includes information about the pore system.

Since the late 1970s, NMR has already been applied to cementitious building materials to study hydration kinetics and pore structure developments [1, 2]. Although, there have been already in situ NMR measurements, for example, on a fresco using a single-sided device, at this time in civil engineering and material research, NMR is still used mainly in the laboratory [3]. Existing devices only have low penetration depths of up to 25 mm and are heavy and, therefore, not easy to manage in the field. Therefore, NMR is more suitable for applications *ex situ* e.g., applications on drilling cores. Nevertheless, NMR enables high resolution of moisture gradients and can provide information on pore size distributions at full saturation non-destructively.

In this paper, we study the capability of NMR and its limitations to determine pore sizes and surface relaxivities of building and synthetic materials. Furthermore, the self-diffusion effects in the applied field gradient shall be qualitatively assessed.

Besides homogeneous synthetic materials e.g., sintered borosilicate glass, this study mainly focusses on the investigation of floor screed. Floor screed (also referred to as "screed") is a composition of sand and cementitious materials or calcium sulfate that is used as a base for floor finish onto the concrete floor. It mainly differs from concrete and mortar due to its maximum aggregate size of 8 mm. In our experiments, we worked with both fully and partially saturated floor screed samples trying to differentiate the relaxation behaviour of fully and partially water-filled pores. For the calibration of the resulting relaxation time distributions as well as the conversion to pore sizes, results are compared to mercury intrusion porosimetry (MIP) and surface relaxivity values from the literature.

In the following pages, two NMR devices and their technical features along with the evaluation methods are described. An explanation of the measurement setup, the investigated materials, and their fabrication where documented, follow in section 2.2. The results are presented in chapter 3 with focus on the development of relaxation time distributions during a saturation process (for floor screed) and the determination of pore size distributions. In the end, the results are discussed and main aspects summed up.

2. Methods and Materials

2.1. Methods

The main method used in this study was proton NMR relaxometry [4]. The measurements were carried out using two different Magritek devices. We first applied a stray field single-sided device model "PM25" or "Mouse" [5]. This device has a measurement area of 4 cm x 4 cm with a vertical resolution of 120 μm . A special feature is the high precision lift which enables measurements at varying depths up to a maximum penetration depth of 24.8 mm. Due to the open magnet construction, the device is characterized by a high static gradient field of about 8 T/m. The minimum echo time is 95 μs .

The second NMR device that was used is the so called "Rock Core Analyzer" (RCA) [6]. The RCA enables measurements of cylindrical samples in a homogeneous field (gradient strength > 100 mT/m) with an echo time of 300 μs . For the used coil, the maximum possible sample dimensions were 101.6 mm in diameter and length.

The evaluation of NMR data was performed using an inversion algorithm that converts the measured decays of transverse relaxation times into relaxation times distribution. Although Magritek's software includes such an inversion function, we used a self-programmed algorithm that was provided by Thomas Hiller (Leibniz Institute of Applied Geophysics). The inversion

is based on the inverse Laplace transformation. In this algorithm, different inversion parameters can be manually adjusted. Especially for the regularization parameter, the L-curve criterion enables a control of the value's choice. Furthermore, the user gets information about the signal-to-noise ratio and the resulting root-mean-squared error. Also, they can decide whether an exclusion of the first echos improves the fitting.

Based on the fast diffusion limit assumption, the final conversion from relaxation time to pore size was applied either using a comparison method such as MIP or the material parameter surface relaxivity was known. According to the fast diffusion limit, the pores are expected to be small enough that protons can cross the whole pore many times within their relaxation process [4]. Therefore, the calculation can be done with the following equation (2.1) [7]:

$$\frac{1}{T_{2,\text{Surf}}} = \rho \left(\frac{S_P}{V_P} \right) = \rho \frac{c}{R_P} \quad (2.1)$$

where S_P/V_P is the ratio of surface area to pore volume [$1/\mu\text{m}$]; ρ is the surface relaxivity [$\mu\text{m/s}$]; R_P is the pore radius [μm] and c is a shape factor [-] describing the pore model, which is assumed to be $c = 2$ corresponding to a cylindrical pore geometry.

This equation results from the simplified transverse relaxation rate when the diffusion and bulk terms are neglected [4, 7]. The component $T_{2,\text{Bulk}}$ is often neglected because in most cases it is long in comparison to the surface relaxation rate, especially in porous materials. For simplification, the diffusion term is ignored as well. Due to the estimated small pore sizes and short relaxation times in building materials like floor screed, the authors expected the time-window for possible self-diffusion effects to be too short. Resulting measurement errors based on this simplification were assumed to be insignificant.

In the case of the screed samples with an unknown surface relaxivity, MIP results from a measurement campaign in the year 2016 were used for calibration [8]. In this study, floor screeds of the same type were measured after hydration according to the international standard [9]. The MIP measurements were done using two devices of the company Thermo Fischer Scientific. The device PASCAL 140 was needed for measurements from 0.1 kPa to 140 kPa. For measurements at high pressure up to the maximum test pressure of 400 MPa, the device PASCAL 400 was utilized. The deduced pore sizes start from a minimum pore diameter of approximately 10 nm up to 50 μm .

2.2. Materials and Set-Up

For this study, we investigated one building material and two synthetic materials non-destructively. The floor screed, as a representative for porous building materials, was an anhydrite bonded screed. According to manufacturer's specifications, the screed's main components are anhydrite, gypsum, quartzsand or grainy natural anhydrit as aggregates. In addition to these, it also contains plasticizers that are not further specified. A mineralogical analysis of the floor screed after hydration by the method X-ray diffraction (XRD) showed that the minerals anhydrite, quartz, calcite, dolomite, and gypsum mainly formed. To better classify the investigated floor screed, an additional chemical analysis of the floor screed samples A1 and A3 was done after hydration using the method Laser-Induced Breakdown Spectroscopy (LIBS). The method LIBS enables a fast and almost non-destructive determination of chemical elements in building materials. Since a calibration for the element iron was performed, we quantified the iron amounts within the samples. For further detected elements only a qualitative estimation was possible.

The LIBS spectra shown in Figure 1 indicate that both screed samples had the same chemical composition after hydration. However, the spectrum of the sample A3 revealed higher intensities for almost all detected elements. Iron and magnesium as possible ferromagnetic and

paramagnetic impurities were the elements of main interest, due to the possibility they might cause a shortening of relaxation processes during NMR measurements [4]. As presented in the enlarged subfigure, the screed samples contained both elements, even when the amount of magnesium was not quantified. Whereas, we obtained an iron concentration of around 0.2 m% in A1 and 0.24 m% in A3. Further elements that were measured are the following: calcium, silicon, potassium, sulfur, hydrogen, and oxygen.

For the experiments, we produced four brick-shaped screed samples with the dimensions 200 mm x 120 mm x 40 mm. They were first measured at the beginning of hydration (day 3) at an almost fully saturated state. Afterwards, the samples were stored in different climates. In this way, the velocity of the hydration process should be influenced and, therefore, the pore system developed differently. The samples A1 and A2 remained saturated in a tank filled with tap water, while samples A3 and A4 were stored in a climate-controlled chamber at ambient conditions of 23°C and 50% rH. It follows that only A1 and A2 had an adequate water supply for hydration reactions.

To obtain information about the pore sizes contributing to the NMR signal at partial saturation, the samples were resaturated or even reduced in saturation after 1.5 months. For reaching defined partial saturation, we stored the samples at different relative humidities. First, all four samples were stored at 80% rH and 23°C until they reached mass equilibrium [10]. The next step was the saturation at 90% rH. To complete each stage, the proton signal of every sample was measured in 9 different penetration depths from 3 mm to 24.8 mm using the NMR Mouse. During the entire measurement campaign, we monitored the weights using a digital balance with a tolerance according to DIN EN ISO 12571 [10].

Having an inert and homogeneous pore system in comparison to most building materials, we also investigated borosilicate glass and a biobased plastic called polylactide (PLA) as synthetic materials. Because of the sinter process, borosilicate glass plates with different pore size distributions could be obtained. PLA, which is used for 3D printing, was chosen because it is an alternative material for the production of specially designed NMR calibration probes. The pore sizes of all used materials as well as the applied methods are listed in Table 1.

In this study, we examined 15 filter plates made of borosilicate glass. Due to sintering as described above, there are three groups with different pore size distributions. The borosilicate samples were flat cylinders and had a diameter of 70 mm. The height was about 5.5 mm. The size and format of the samples was suitable for accurate coverage of the measurement area of the NMR Mouse and they also fitted well into the coil of the Rock Core Analyzer. At this point, it should be noted that the RCA instrument, which is the property of a different institute, was applied as a supplementary measurement to clarify some recognizable diffusion effects.

For the measurements using the NMR Mouse, two samples of each group were stacked and placed into a glass of demineralized water. After two days of saturation, the samples were expected to be fully saturated. The samples had a high porosity and the penetrated water did not seem to be held within the pores (when the samples were removed from the water, immediate outflow was observed). Therefore, no weight control was realized, and they were measured while remaining in the tank of water at a penetration depth of 10 mm. For comparison, the NMR measurements of the borosilicate glass plates were repeated using the RCA. The measurements using the RCA were carried out for 3 samples of each group. Every sample was measured separately at full saturation. Due to the construction of the device, the samples were measured while wrapped in a thin plastic foil to prevent moisture transport and drying. For evaluation, the results within one group were averaged.

Polyactide was the last material to be investigated. Two samples with different structures were measured at full saturation (within a tank of demineralized water) using the NMR Mouse. For both samples, the measurement depth was 7 mm. One specimen was characterized by a honeycomb structure; the second one seemed compact with unknown pore sizes. Subsequent

destructive tests showed that the second PLA piece included many large voids inside. Measurements using the RCA were not possible for the PLA samples because they did not fit into the coil.

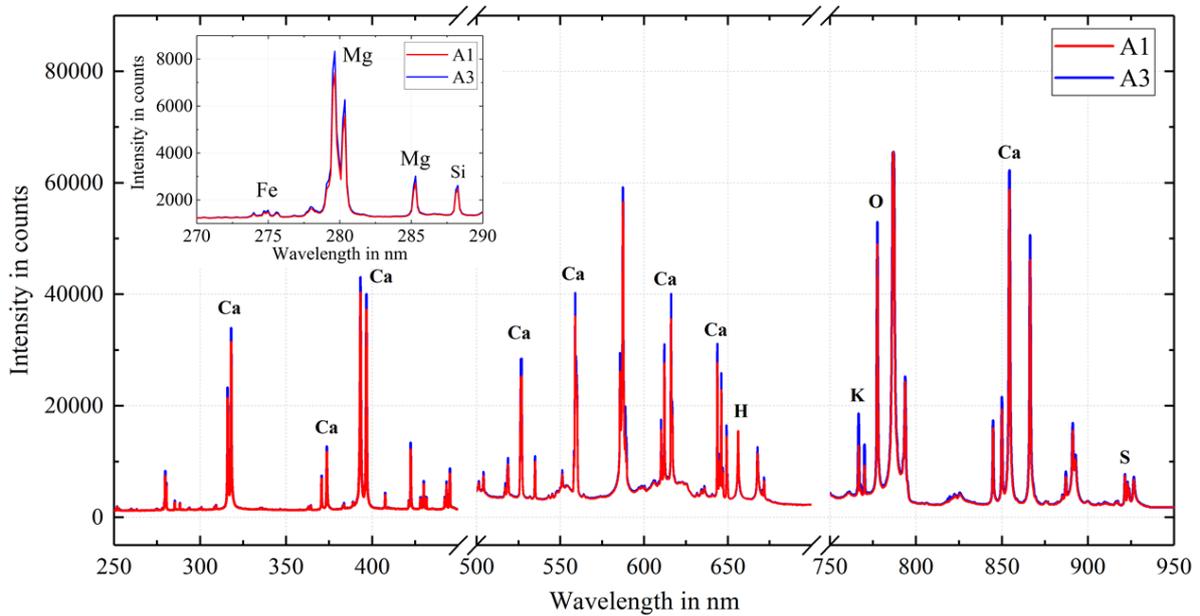


Figure 1: LIBS spectra of the floor screed samples A1 and A3; the subfigure shows the enlarged spectra of iron and magnesium from 270 nm to 290 nm.

Table 1: List of investigated synthetic and building materials, pore size distributions, and the applied methods.

Specimen	Pore sizes [μm]	Methods
Filter plates (sintered glas)	P5	NMR (Mouse, RCA)
	PF	
	P4	
Polyactide (PLA)	2500	NMR (Mouse)
Anhydrite screed	A1	MIP, NMR (Mouse)
	A2	
	A3	
	A4	

3. Results

3.1. Relaxation Time Development during Resaturation Process

As described above, four screed samples were studied using a single-sided NMR device at different saturation states. The arithmetic mean over the sample depth was calculated for every measurement.

In Figure 2, the transversal relaxation time distributions and their standard deviations at three different saturation levels are presented. The NMR measurements on the floor screed were performed at almost fully saturated state immediately after preparation and after storage in a climate chamber at 80% rH and 90% rH. At full saturation (blue), the results show a wide distribution of relaxation times from 0.001 s to 1 s. The highest probability was measured for relaxation times between 0.005 s and 0.01 s. Major differences between the four screed samples were not observable at full saturation.

At partial saturation, the relaxation time distributions differ from the results at full saturation. In comparison to the saturated state, distributions of relaxation time were significantly shifted towards lower times of around 0.01 s down to (the measuring limit of) 0.0001 s. The highest signal component came from relaxation times close to 0.0004 s. The maximum probability value decreased with reducing saturation though. A comparison of relaxation time distributions at the partial saturation state after storage at 80% rH and 90% rH showed almost similar curve characteristics for all samples. Nevertheless, deviations of the probabilities were noticed when comparing the single curves within one saturation state with each other. At both partial saturated states the higher probabilities resulted from the samples A1 and A2.

The arithmetic mean of 9 measurements over the entire range of the sample's depth resulted in large standard deviations. Especially in the range of higher probabilities, we observed large standard deviations. Moreover, the standard deviations at partial saturation state seemed larger than at full saturation. However, significant differences between the deviations of single screed samples could not be registered.

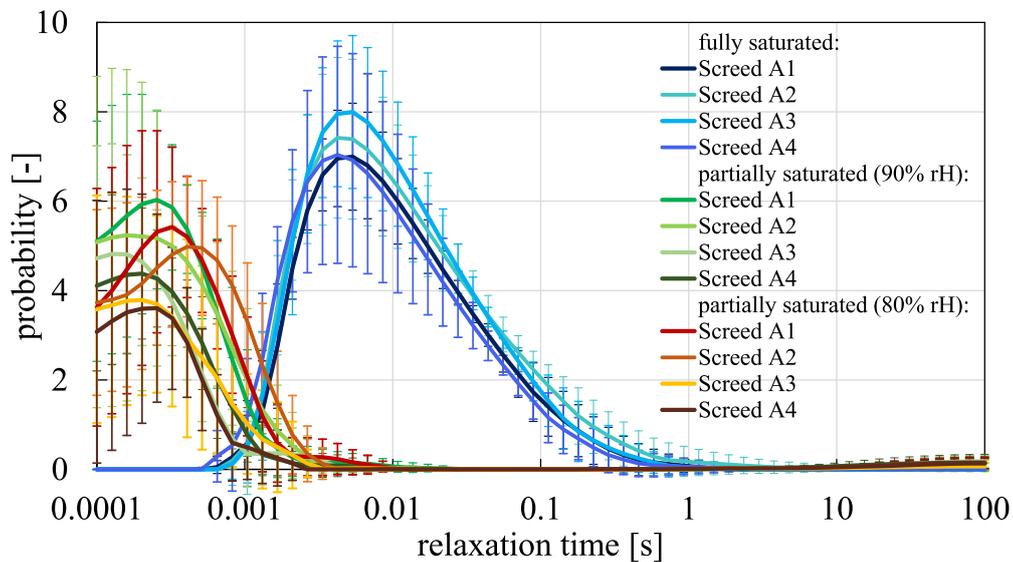


Figure 2: Transversal relaxation time distributions and standard deviations of screed samples at different saturation levels (arithmetic mean of 9 measurements between 0 mm and 24.8 mm depth).

3.2. Determination of Pore Size Distribution and Surface Relaxivity

To convert the relaxation rates of the screed samples to pore sizes, the measured relaxation time distributions were referenced to MIP data with the same procedure as explained in Wang et al. (2017) [11]. The NMR relaxation times were presented cumulatively and then compared to the MIP results from Kruschwitz et al. (2017) [8], which indicate the cumulative pore volume over pore diameter. According to equation (2.1), the authors varied the parameter surface relaxivity until the best fit to the MIP results was obtained (see Figure 3).

To achieve information about the entire accessible pore space within a sample using proton NMR, the sample needs to be fully saturated. This means, specifically, that every single pore has to be completely filled with water. However, when considering a partially saturated material, the pores only contain water films (water layers) on the pore wall or the water is trapped in corners [12, 13]. Within these water films and pore corners, the relaxation processes of protons are extremely shortened due to higher interaction rates with the pore wall. To determine the complete pore size distribution of the floor screed, the use of NMR was therefore only possible at full saturation state.

The pore sizes of the anhydrite screed samples could be determined to extend from 0.03 μm to 5 μm . The dominant pore sizes were in a range of 0.3 μm and 2 μm . This result was achieved

with a surface relaxivity of $50 \mu\text{m/s}$. However, in the literature, building materials are reported to feature similar surface relaxivities to natural rocks, determined by comparison with gas adsorption based on the Brunauer-Emmett-Teller theory (BET); results were between $0.5 \mu\text{m/s}$ and $10 \mu\text{m/s}$ [14, 15].

The distribution of relaxation times measured at partial saturation are also presented in Figure 3. Assuming that the material composition did not significantly change due to late hydration, a conversion to pore sizes was done using the same surface relaxivity value. In this case, we assumed that only smaller pores remained saturated and contributed to the NMR signal, whereas larger pores were only partially saturated or completely emptied [16].

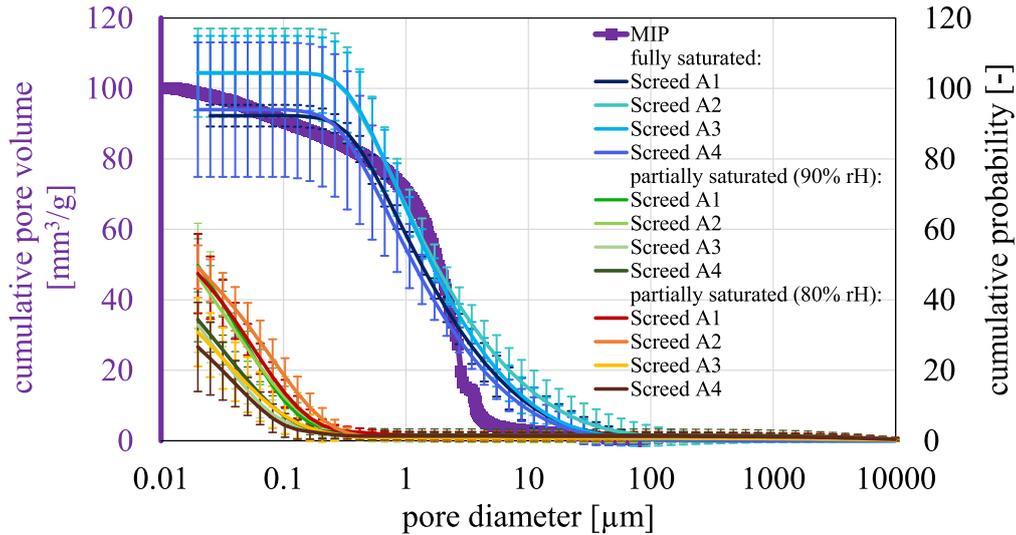


Figure 3: Pore size distributions as obtained with MIP and NMR ($\rho = 50 \mu\text{m/s}$) on screed samples at different saturation levels (arithmetic mean of 9 measurements between 0 mm and 24.8 mm depth).

The next step in this study was the determination of pore sizes in the borosilicate glass plates using NMR data and a reference surface relaxivity value from literature for conversion. As can be seen in Figure 4, all measurements that were done with the NMR Mouse show the similar distributions (solid lines). The results indicate wide distributions ranging from $0.1 \mu\text{m}$ to $2 \mu\text{m}$ for all three specimens that do not fit the manufacturer’s specifications (see Table 1 and bar charts). A repetition of the measurements using the RCA device (homogeneous field) led to different results, which are presented as dashed lines in Figure 4. Indeed, using the surface relaxivity value from Mohnke (2014) [17], the determined pore size distributions agree with the manufacturer’s specifications for the specimen P5 and PF. We observed a slight underestimation only for the specimen P4 which had the largest pore sizes of up to $16 \mu\text{m}$.

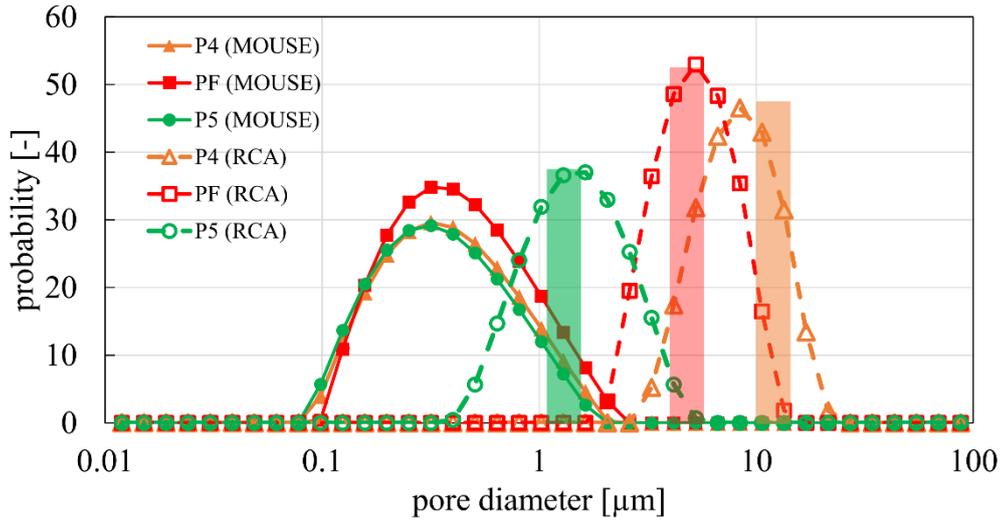


Figure 4: Pore size distributions of borosilicate glass plates calculated from NMR data using a surface relaxivity of $\rho = 1.8 \mu\text{m/s}$ [17]; manufacturer’s specifications (listed in Table 1) are presented as bar charts.

Lastly, the relaxation times of the PLA samples in Figure 5 indicate a pore size distribution that is similar to that of the borosilicate glass plates when measured with the NMR Mouse. An additional comparison of pure water measurements clarified that the hydrogen signal within the PLA samples was the same as of pure water. As the PLA samples (especially the honeycomb structured sample) had large pores or rather voids, the relaxation times were the same as for pure water. Also, although the compact PLA sample was expected to be nonporous and dense, the measurements led to the same relaxation times distribution but with lower probability (solid lines in Figure 5). After we later divided the sample by sawing through, large voids with a diameter up to 6 mm were revealed inside of it. Hence, the compact PLA sample has proved hollow and the fast diffusion limit was no longer applicable.

A comparison with pure water measurements using the RCA proved that the relaxation times of the PLA samples and pure water measured with the single-sided device seemed shifted due to possible diffusion effects. As already known, the transverse relaxation time of water is in the range of seconds (dashed line in Figure 5). Since the PLA samples did not fit into the coil as described above, measurements with the RCA were not done on these.

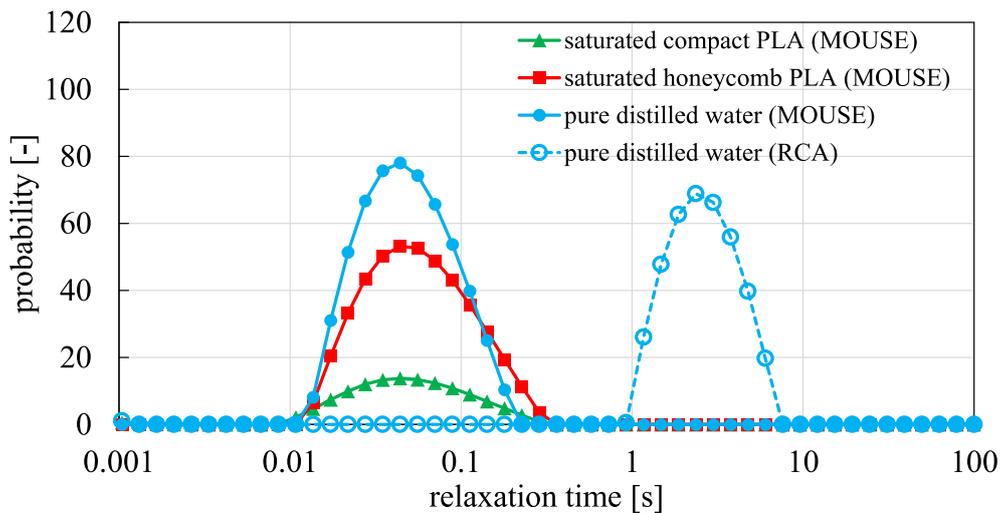


Figure 5: Transverse relaxation time distributions of compact and honeycomb PLA compared to pure distilled water.

4. Discussions

The results presented above show that NMR enables a non-destructive monitoring of relaxation time distributions for different saturation states. The final conversions of NMR data to pore size distributions were done for the floor screed samples and glass filter plates using two different approaches. While the resulted value of the screed's surface relaxivity was higher than suggested by literature, the measured NMR relaxation times of the synthetic materials were strongly shortened when using the single-sided device. In the following, the authors discuss various reasons to explain the occurred phenomena.

The temporal development of the relaxation time distributions as shown in Figure 2 indicate a shift towards lower relaxation times with decreasing saturation. In general, the authors explain this observation by the emptying of larger pores during the drying process. This assumption means, that at a partially saturated state, the NMR signal mainly arises out of small pores or even partially saturated larger pores. In the latter case, the pores only contain a defined water layer. This means that the remaining water is strongly bonded to the pore's surface and therefore relaxes much faster. The same aspect may be recognized in Figure 3 where the data is converted to pore sizes. Even when the author's assumption explains the observed shift, a clear distinction of proton signal between fully saturated smaller pores and partially saturated larger pores still cannot be done. Furthermore, partial saturation often is not considered in pore model representations. Therefore, the assumption of a constant surface relaxivity value at different saturation states remains uncertain and needs to be clarified by further investigations.

Before we discuss the pore size determinations of the examined materials, two more observations from Figure 2 may be mentioned. First, higher probabilities resulted from the samples A1 and A2 than from A3 and A4. This phenomenon could be caused by higher amounts of hydrogen that were built-in and stored within the samples A1 and A2 due to their storage while hydration. Second, the large standard deviations in the range of higher probabilities as well as at partially saturated state might be explained by strong heterogeneities within the screed samples (e.g., aggregates and magnetic impurities) and/or reduced signal-to-noise ratio with decreasing water content.

As described above, for the measurements of the floor screeds, the results showed a surface relaxivity that is higher than first suggested by literature. Dalas et al. (2014) investigated the surface relaxivities ρ of cement hydrates and determined values in a range of 1 $\mu\text{m/s}$ to 6 $\mu\text{m/s}$ [15]. The only component reaching higher surface relaxivities up to 44.7 $\mu\text{m/s}$ was the mineral ettringite which might have an influence on the resulting total surface relaxivity of the investigated screed samples. However, the chemical composition of the investigated floor screed proved that ettringite could not form due to a missing aluminate phase.

The authors see one main reason for the high surface relaxivity value in the choice of the comparison method. As described in Borgia et al. (1996) [14], ρ depends on the resolution of the chosen method. Therefore, it is known that MIP is a more widely accepted tool for pore throat size determination [18]. Further comparison methods such as BET or microscopy techniques did not come into consideration yet in this study. BET was not used because it is limited to a pore size range up to 100 nm [19]. On the contrary, microscopy techniques could be helpful in overcoming of MIP limitations [20]. According to recent findings of Zhang et al. (2018) [21], X-Ray microtomography is rather applicable to determine the size of pore bodies than of pore throat sizes. Furthermore, NMR is also told to be more sensitive to the pore body size, so the surface relaxivity value may be still higher [21]. Nevertheless, due to the drawbacks of the application of microscopy techniques and X-Ray microtomography (required experience for the evaluation, sample size and representativeness), it was not applied in this study.

In addition to the limitations of comparison methods, another explanation for a higher surface relaxivity could be the influence of ferromagnetic impurities or even paramagnetic ions like iron within the sample. As the chemical analysis of the screed samples showed, they indeed

contained amounts of iron and magnesium. However, Sharma et al. [3] proved that ferromagnetic impurities are less likely to be encountered in the thin measurement volume of the NMR Mouse. The influence of paramagnetic ions in our case could not be estimated yet. To clarify these influences, further studies require more quantitative analyses (in situ during hydration) of the chemical composition as well as supplementary NMR measurements with various settings.

One important observation during measurements of the synthetic materials using the NMR Mouse was the shift to lower relaxation times (see Figure 4 and Figure 5). In comparison to the measurements with the RCA, it can be assumed that the measurements failed due to the effect of diffusion in the gradient field (8 T/m). This effect may only occur in magnetic gradient fields and it seems to depend on the sample's pore sizes. For samples with pore sizes that no longer allow the assumption of the fast diffusion limit, diffusion processes shorten the relaxation times significantly. The chemical composition and materials parameters like the surface relaxivity itself were assumed not to have any influence on the resulted diffusion effects. However, in this case, the simplification of equation (2.1) was incorrect because the influence of the diffusion term was still measurable and significant. This knowledge is important for further studies. It must be clarified if and how these effects can be corrected and rather they can be used for getting information about microstructures.

According to the inversion results, it must be said that errors resulting from the inversion calculation itself cannot be excluded. Especially measurements in partially saturated floor screed showed bad signal-to-noise ratios and, therefore, led to complications while data fitting. The inversions showed also strong dependencies on the choice of the regularization parameter.

While the influence of the chemical composition of the investigated synthetic materials was excluded, until that point no further considerations was made about chemical reactions (on surface site) in the hydrating system of the floor screed. The main reaction assumed to take place while hydration was the conversion from anhydrite to gypsum. This reaction results in a high conversion rate from free or physically bonded to chemically bonded water. The main problem here was due to the relative high echo time of about 95 μ s of the used single-sided device. Signal parts caused by chemical bonded water (very short relaxation rates) cannot be recorded in comparison to some parts of physically bonded (e.g., adsorption) and free water. Therefore, a clear distinction of the different water fractions contributing to the NMR signal was not possible in this study. In the case of drying or saturation processes, a change in the water film thickness also can result in a change of the water's physical property.

To clarify the unanswered questions dealing with the above described chemical developments within a building material, further studies of various methods are needed to supplement NMR. The authors see the non-destructive distinction between physically and chemically bonded water fractions and, consequently, the extension of NMR applications to partially saturated pore systems as future main focuses.

5. Conclusions

In this study, NMR (mainly using a single-sided device) was applied as a non-destructive tool to building and synthetic materials. The main goal was the determination of pore size distributions. Furthermore, we investigated the possible influences as well as sources of error depending on the chosen material and preparation.

The monitoring of relaxation time distributions at different saturation levels in this study were quite successful. On the contrary, the determination of pore size distributions on hydrating screeds left some questions unanswered. We observed higher surface relaxivity values than expected of about 50 μ m/s which might be influenced by ferromagnetic impurities, affected by chemical interactions while hydration or is due to the used comparison method MIP. In addition to that, the behavior of the surface relaxivity at partially saturated state and during hydration

processes requires more investigations. A clear distinction of the proton signal at partial saturation also remains still an open question.

In this work, the investigations with the NMR Mouse on synthetic materials were affected by occurring diffusion effects while measuring within the existing magnetic gradient. Especially, when comparing the results with measurements of pure water these effects were very striking. Further studies require a better quantification of these effects and possible corrections.

Specific optimization suggestions for the presented experiments in this paper are the following: a) the measurements on screed need repetitions and new resaturation to estimate the influences of hydration; b) performance of chemical in situ studies of the floor screed samples; c) a control of pore sizes of the borosilicate glass plates by doing MIP and further comparison method. For the future in general, a better understanding of chemical reactions, and therefore, the changing composition that occurs during the process of hydration of building materials is indispensable. According to the used MIP results, for further experiments different reference methods should be taken into account as well.

In conclusion, it can be said that NMR, depending on the investigation material and the technical aspects of the used device, is suitable for special applications according to pore space characterization in civil engineering. Although still mostly applied in a laboratory, NMR (especially using single-sided devices) has a high potential for non-destructive resolution and characterization of moisture transport and the relevant material parameters.

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