

HYDRATION AND EARLY-AGE STRENGTH MEASUREMENT OF CONCRETE USING NUCLEAR MAGNETIC RESONANCE (NMR)

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A new nondestructive technique for monitoring the hydration process of cement within concrete and measurement of the compressive strength of concrete is presented. The technique called the Nuclear Magnetic Resonance (NMR) has so far been primarily used in the fields of chemistry and medicine. Its application to construction materials has been very limited or nonexistent. In this study, NMR is used to monitor the hydration of cement paste in concrete with two different water cement ratios. The first objective of this study was to distinguish between the amounts of remaining free water, and water consumed in the hydration process during the 28 days monitoring period. The second objective was to relate the compressive strength of concrete to NMR signals. A number of standard compression tests were performed in parallel with the NMR tests. Correlation of the responses from nondestructive tests with NMR and those of standard compression tests indicated almost a linear relationship.

KEY WORDS: NMR, concrete, hydration, strength measurement.

INTRODUCTION

Hydration of cement in concrete plays an important role in curing and development of concrete properties. Careful monitoring of this process will help researchers and engineers to better understand the behavior and properties of concrete and to improve its response to loads and environmental factors. In this paper, a new technique with a potential for monitoring the hydration process of cement in concrete and its relationship to the compressive strength is presented. The technique which utilizes the sub-atomic properties of constituent materials is called the Nuclear Magnetic Resonance (NMR). NMR has been extensively used in a variety of disciplines such as chemistry, biology, medical imaging, etc. However, its application for testing of construction materials has been very limited if any at all. Presently, NMR is probably the most powerful material analysis technique in biochemistry and analytical chemistry. In medicine, imaging by NMR is becoming increasingly popular as an effective diagnostic tool in recent years.

In subsequent sections, a brief introduction to the principles of NMR will be given. The results of NMR tests performed on concrete samples with two different water cement (W/C) ratios during the first 28 days will be discussed. In addition to the NMR tests, standard compression tests were also performed on 100 mm × 200 mm

(4 in. \times 8 in.) cylinders of concrete from the same batch. Both the NMR and compression tests were performed at the same time. The results of the destructive and nondestructive tests were compared and correlated. Such correlations can be used to calibrate the NMR response for nondestructive evaluation of in situ properties of concrete in the field.

RESEARCH SIGNIFICANCE

Considering the potentials of NMR as an effective technique for monitoring the hydration of cement within concrete and as a new nondestructive technique for evaluation of in situ mechanical properties of concrete such as the compressive strength, this research could form the basis for a new generation of equipment and methodologies for testing and understanding of the behavior of concrete. In particular, with the growing concerns over the status of infrastructure and the limited resources available for the rehabilitation of structures, NMR could present new possibilities in the area of nondestructive testing to identify those structures most in need of rehabilitation.

PRINCIPLES OF NMR SPECTROSCOPY

As with all types of spectroscopy, an NMR response yields spectra that can be described in terms of the frequency, magnitude, and shape of the lines or bands. In this section, a brief summary of the principles governing the NMR technique as reported by several authors [1 to 4] is presented.

The nuclear spin of atoms in materials is the primary phenomenon in NMR spectroscopy. Essentially some nuclei can be thought of as tiny spinning particles. Since nuclei are charged particles, their spinning creates a magnetic field around the nucleus, which is called a magnetic moment. The magnetic moment (μ) is a measurable vector quantity which can be used to describe the strength and direction of the magnetic field. The magnetic field of a spinning nucleus is analogous to the magnetic field of a tiny bar magnet [1].

In general, the direction of the spins of protons will be oriented randomly. However, when placed in an external magnetic field, B_0 , the nuclei will all try to line up with the direction of the field as shown in Figure 1. The orientation of the protons will either be parallel or anti-parallel to the magnetic field, as shown in the figure. Furthermore, quantum mechanics shows that for protons (the principal isotope of hydrogen) the spin does not align exactly with the external magnetic field, but rather it tilts at an angle θ , as shown in Figure 2. The magnetic dipoles then begin to precess about the direction of the external field. The precessional movement of the magnetic moment vectors form the surface of a double cone as shown in Figure 3.

Although the spinning protons attempt to line up with the magnetic field, they never actually achieve this. This can be understood by considering the classical motion of a magnetic moment in a magnetic field. The magnetic field, B_0 , will create a torque on the magnetic moment, μ , equal to the cross product of the two vectors,

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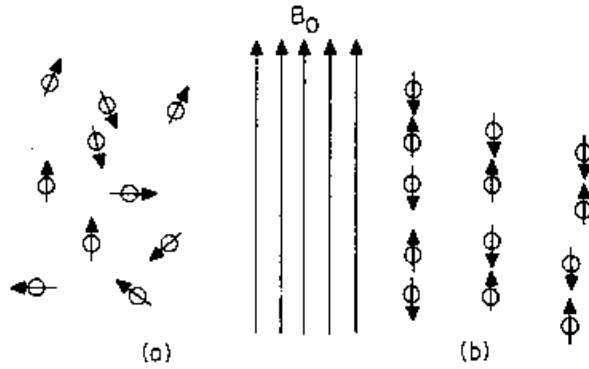


Figure 1 Nuclei Orientation: (a) in the Absence of External Magnetic Field; (b) in their Presence of External Magnetic Field (McMurry, 1988).

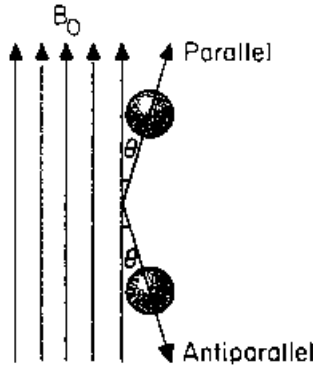


Figure 2 Inclination of Magnetic Moment with Respect to External Field.

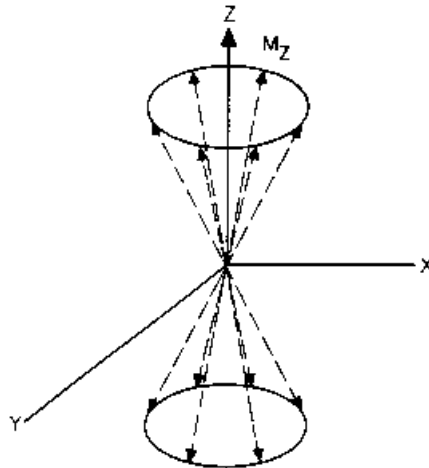


Figure 3 Precessional Motion of Magnetic Moments. Due to Random Phases, Transverse Components of Individual Spins Cancel Out.

$$\tau = \mu \times B_0 \quad (1)$$

Since this is a cross product, the torque will only alter the component of the angular momentum perpendicular to μ and B_0 . Therefore, the magnetic moment will rotate about B_0 at an angle θ , and will trace out a cone about B_0 . In other words, the spinning proton will be pulled towards the direction of the external magnetic field, but will precess about it instead. This motion can be thought of in terms of spinning top. The top will never line up perfectly with the force of gravity, but will wobble slightly about it (precession). The top would wobble faster if the gravitational forces were increased, just as the proton will precess faster if the magnetic field is increased [1].

It should be noted that the rate of precession depends also on the type of nuclei. In fact, the angular velocity of precession, also called the Larmor frequency, is equal to the product of the magnetogyric ratio (a characteristic material constant), γ , and the magnetic field, B_0 [1]:

$$\omega_0 = \gamma B_0 \quad (2)$$

It is at this point that the phenomenon of resonance can be understood. If an additional weak magnetic field, B_1 , supplied by a radio frequency (RF) through a coil wrapped around the sample, is applied in a direction perpendicular to B_0 , it will also apply a force on the magnetic moment. Since the direction of B_1 is fixed, it will alternately try to increase and decrease the angle θ as μ travels around the cone (with frequency ω_0). However, if the B_1 field is rotating at exactly the same frequency as the precession of μ , then the field will "pull" on the magnetic moment at all times. This coherent force pulls the magnetic moment away from B_0 , and causes it to flip to the anti-parallel energy state. This is what is called "resonance."

Magnetic resonance signals can only be received if transverse magnetization — that is, magnetization perpendicular to B_0 — is created, since it is the transverse component, M_{xy} , which is time dependent and thus according to Faraday's Law of Induction can induce a voltage in a receiver coil. Transverse magnetization is created if a radio frequency field of amplitude, B_1 , in resonance with the precessing spins is applied in a direction perpendicular to the main field. If the duration of the B_1 field is such that the net magnetization is rotated by an angle of 90 degrees, it will become transverse, that is, perpendicular to the static field, B_0 [1].

Before a system is perturbed by a radio frequency, all the magnetization occurs along one axis, let's say z axis. At this stage, the transverse components of the magnetic moment cancel each other, i.e., $M_x = M_y = 0$. But in order to obtain resonance, the system must be perturbed. This is done by passing an RF alternating current through a coil wrapped around the sample space as shown in Figure 4. At this time, the nuclear moments do not have the same components in the xy-plane. Therefore, they can no longer cancel out and there will be a resultant magnetization, M_{xy} , transverse to the external field [2]. The magnetization is no longer static and the rotating vector M_{xy} induces an RF current in the coil around the sample which can be measured as a signature for the material being tested. It is noted that the net magnetization is of interest, i.e., the magnetization for the whole sample.

Relaxation

If a system is perturbed, the system will relax back to its ground state. The relaxation time is denoted by T.

In NMR, the relaxation time T is slow, T₁ and T₂ are the two main relaxation times. T₁ is the longitudinal relaxation time and T₂ is the transverse relaxation time. Both are extremely important in NMR spectroscopy.

Spin Lattice

For a system in a magnetic field, the spins will align with the field. When a system is perturbed, the spins will flip to the (-z) direction. The magnetization will then relax back to its ground state. However, the relaxation time is not the same for all spins.

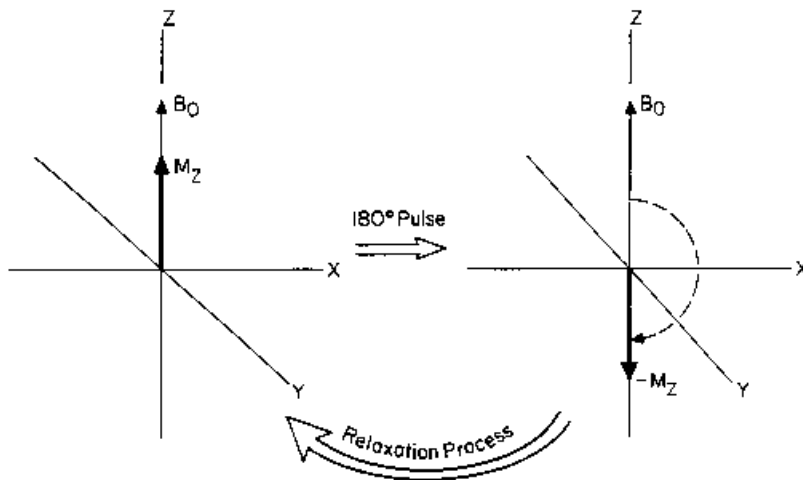


Figure 5 Pulse Sequence for Measuring T_1 .

In order to monitor the spin-lattice relaxation, a pulse sequence called inversion-recovery is used. A 180° pulse is first applied to invert the magnetization. After a very short time, τ , a 90° pulse is applied which rotates the magnetization into the transverse plane. The resulting signal is monitored and the T_1 is measured.

Spin-Spin Relaxation Time (T_2)

After the magnetization is rotated into the transverse plane, the NMR signal decays because the transverse component of the magnetization decays. However, the decay of the signal takes place even faster than expected due to the inhomogeneity of the magnetic field. In other words, since the magnetic field is not homogeneous, each nuclei will experience a slightly different field. The different fields will cause nuclei to precess either faster or slower than assumed. As a result, some magnetization vectors advance faster than others and the magnetization "fans out", as shown in Figure 6 [2]. This causes the transverse magnetization to decay more quickly. The time constant associated with this process is called T_2 .

The inhomogeneity of the magnetic field is caused by inhomogeneities of the magnets themselves as well as the spatial locations of the nuclei.

Free Induction Decay (FID)

Upon removal of the perturbing influence or the radio frequency field the magnetization is subjected to the effect of the external static magnetic field only, and hence, precesses about it. During the post-excitation period or "free precession" period after the RF field has been removed the magnetization induces a voltage in the receiver coil placed in the transverse plane. The transverse magnetization, M_{xy} , causing the induced voltage, will decrease to zero with the characteristic time, T_2 , and so does the

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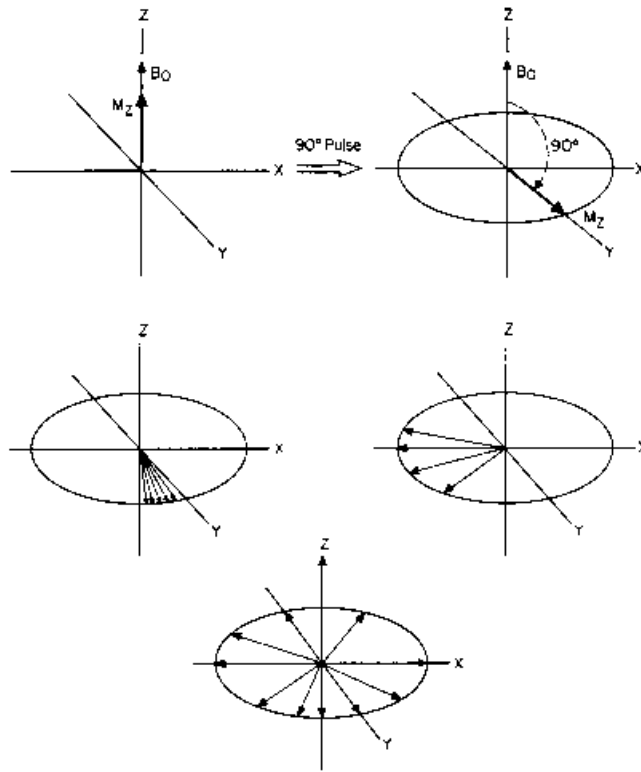


Figure 6 Pulse for Measuring T_1 and Out of Phase Transverse Magnetization Due to Random Precession Frequency.

amplitude of the detected voltage [1]. The signal received in this process is termed "Free Induction Decay (FID)." This signal is in the form of a damped oscillation. The initial signal amplitude is proportional to the transverse magnetization. Because the transverse magnetization itself is proportional to the number of nuclei excited in a particular sample, the differences in the hydrogen density becomes discernible in the NMR response [1].

It should also be mentioned that the values of T_1 and T_2 may be equal or they may differ by orders of magnitude, but T_2 is always shorter than T_1 because M_{xy} decays much faster than M_z is reestablished. The signal derived from M_{xy} disappears well before the equilibrium is achieved.

The Carr-Purcell Pulse Sequence (Spin Echo)

In practice, the magnetic field generated by electro- or super-conducting magnets has always some degree of inhomogeneity. The effective or observed value of T_2 , defined by T_2^* which includes the effects of the magnetic field inhomogeneity is always shorter than T_2 . Another factor affecting T_2 is a random relaxation field caused

by the interaction among the tiny magnetic fields of the nuclei themselves. The phenomenon is intrinsic and is independent of the instrumental imperfections. These two processes are different in that the first one acts continuously and is constant at each part of the sample so that in principal it can be corrected, while the second one is random and unpredictable and cancels out [2]. Accurate estimates of T_2 , however, are obtained using a spin-echo measurement called the Carr-Purcell pulse sequence.

If a 90° pulse is applied, all the magnetization M_{xy} is in the xy plane, but different parts of the sample have different angular velocities due to the inhomogeneities of the magnetic field. Consequently, some spin-nuclei move ahead of the average angular velocity while some others lag behind. After discontinuation of the 90° pulse, the transverse magnetization M_{xy} will decrease and may even become zero if magnetic field inhomogeneity is large. The initial transverse magnetization, however, can be reestablished after a time lapse τ seconds by turning the partially dephased magnetization over into a mirror image position. This is accomplished by applying a 180° RF pulse along x , τ seconds after the initial 90° pulse. The nuclear spins continue to precess, but after another τ seconds, they will come into phase and the transverse magnetization M_{xy} will again reach a maximum [2]. The 180° pulse is a refocusing pulse and the intensity of the spectrometer output rises following this pulse to a maximum τ seconds after, and then it decays again. Subsequent 180° pulses will refocus the magnetization, which could be refocused indefinitely if the applied pulses were perfect. The refocusing does not work for the random relaxation process. As a result, the duration of the experiment is limited by intrinsic transverse relaxation. In fact, the echoes decay in intensity at a rate determined by the real T_2 , which can be measured from a plot of intensity versus time. The significance of these echoes will become more clear in subsequent sections on applications of NMR where T_2 s are determined for concrete samples.

H-NMR Spectroscopy

The hydrogen proton due to its simplicity and relative abundance lends itself very well to NMR spectroscopy. In fact, it is often given its own branch of NMR called proton- or H-NMR spectroscopy. The intensity or height of the signal is proportional to γ^4 , where γ is the magnetogyric ratio [4]. Hydrogen proton has the second-highest magnetogyric ratio known and therefore this explains why it is so popular for NMR experimentation.

Chemical Shift

Another phenomenon that needs to be referred to is called the "chemical shift." Without this phenomenon the application of NMR would be limited. Different nuclei would resonate at different frequencies due to variation in γ , but these differences would be hard to quantify. The chemical shift arises because of the way that the electrons shield or screen the nuclei from the external magnetic field. This shielding can be quantified. Furthermore, electron motion can be related to the position of a nucleus in a molecule. It follows that the position of a nucleus in a molecule can then

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be related to the electron shielding. As a result, the chemical shift causes the NMR signal to behave slightly differently for nuclei in different chemical environments. It is this slight difference, for example, that makes it possible to distinguish protons in free water molecules from proton in bond hydrogen in concrete. These differences exhibit themselves in NMR signals, as will be demonstrated in subsequent sections.

Previous Works

Several researchers have used NMR to investigate the hydration and chemical reactions taking place between water and cement. However, no report was found on relating the mechanical properties of concrete, such as the compressive strength to the NMR response.

Blinc and Lahajnar [5] performed spin-lattice magnetization recovery measurements of exchangeable water in ordinary Portland Cement (OPC) and white cement. Such measurements allowed for an almost continuous monitoring of the evolution of the fractal geometry of cement gels with hydration time.

Schreiner and MacTavish [6] studied the spin-lattice relaxation time of hydrated cement pastes. The results obtained allowed a characterization of the fraction of water protons relaxing toward the lattice with different relaxation times T_1 .

MacTavish and Miljkovic [7] compared the behavior of white cement (small iron content) and OPC (containing Fe_2O_3) using NMR. Both types of cement were mixed with doubly distilled water in the ratio 0.42 g water/g dry cement. The results indicated that the loss of signal from protons in the liquid-like environments in OPC is significantly different from the corresponding loss in white cement. The difference between the liquid water signals from these two samples is the result of the strong magnetic interaction between the Fe atom's electric spin and the water in its vicinity.

Rumm and Haranczyk [8] investigated the use of NMR in hydrating cement to differentiate between protons which were in liquid phases and those embedded in the rigid structure. The FID of the protons was measured at 30 MHz room temperature. From the results of the tests, they concluded that NMR can be used to quantify the amount of water consumed by the cement matrix.

Lasic and Corbett [9] studied the spin grouping of NMR to investigate the composite proton signals in solidifying cement paste. The experiments were performed on synthetic white cement samples ($W/C = 0.42$) at room temperature. Using the NMR signals, they were able to distinguish between the water molecules in the coatings and among the hydrated cement grains, and the water molecules in the gel and the crystalline products.

SAMPLE PREPARATION AND TESTING METHOD

Two types of tests were performed: nondestructive NMR tests and standard compression tests. The samples were prepared using two different W/C ratios: 0.42 and 0.62, by weight. All samples were prepared using OPC Type I-II. The maximum aggregate size was 9.5 mm ($\frac{3}{8}$ in.). Standard 100 mm \times 200 mm (4 in. \times 8 in.)

cylinders were cast for the compression tests. Samples for NMR testing were placed in 15 mm diameter by 125 mm high ($\frac{3}{8}$ in. diameter by 5 in. high) test tubes. It was very important that the concrete samples contained in the test tubes would replicate as much as possible the mix and moisture content of the samples contained in the cylindrical plastic molds for destructive compression tests. Consequently, the concrete used to make both kinds of samples came from the exact same mix. Furthermore, in order to keep the level of total water content constant, both cylindrical and test tube samples were sealed with a layer of paraffin wax and they were all kept in a room with constant temperature. Figure 7 shows a typical NMR test tube sample.

The compression strength tests and the NMR tests were performed at the following times (hours) after the cement and water had been combined to initiate the hydration process: 6, 12, 24, 28, 72, 168, 336, 504 and 672 hours (28 days).

The NMR samples were tested in a 20 MHz NMR spectrometer. The samples were placed inside an NMR probe surrounded by an external static magnet and wrapped with a coil for inducing and receiving RF signals as shown in Figure 8. A schematic of the 20 MHz spectrometer used for the NMR samples is shown in Figure 9. Figure 10 is an illustration of the graphic display generated by the spectrometer when scanning the sample. Due to the high degree of inhomogeneity in the samples, the FID curve (total intensity of magnetization) presented a very fast

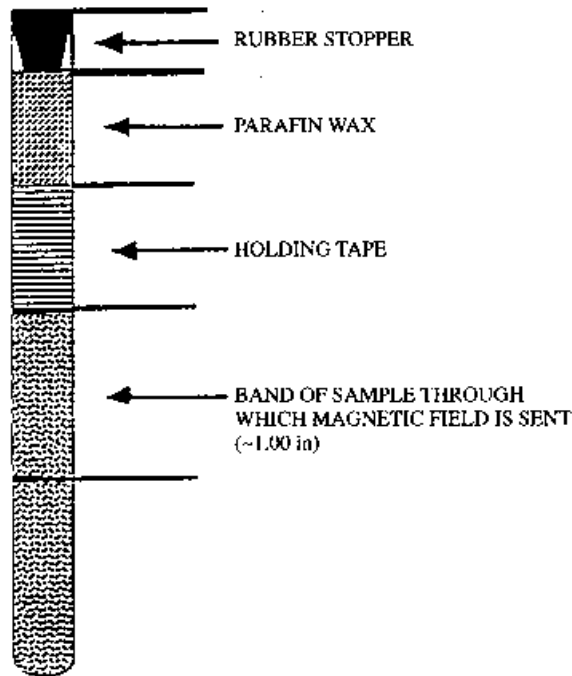


Figure 7 Concrete Samples Used for NMR Testing.

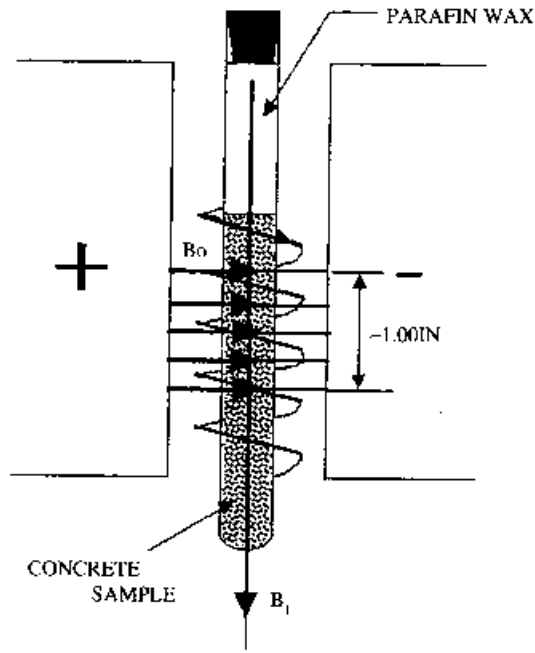


Figure 8 NMR Samples Subjected to Magnetization.

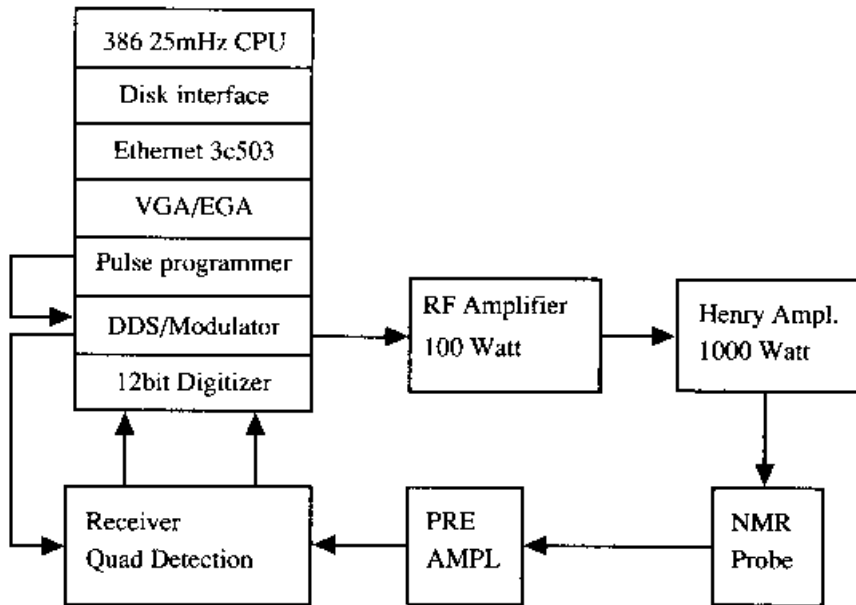


Figure 9 Schematic of 20-MHz Spectrometer.

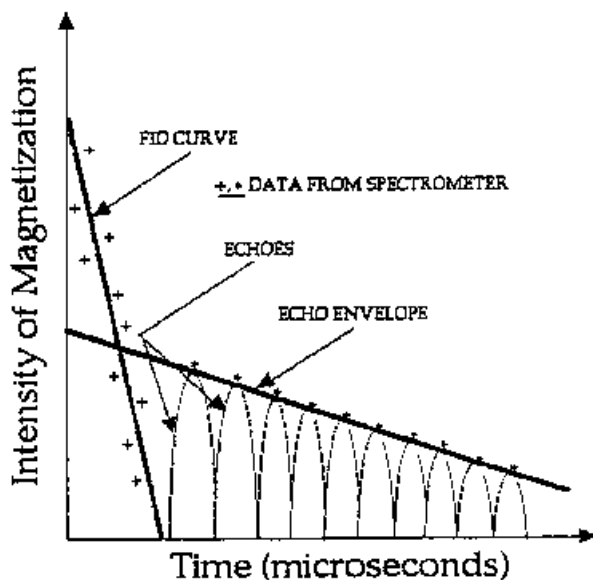


Figure 10 Schematic of Display Generated by NMR Testing.

decay. Once the FID curve had decayed completely, the magnetization of the free water would be brought back by using the Carr-Purcell sequence previously discussed. For every time that a cycle of the sequence was completed, an echo would be generated. However, due to the inhomogeneity effect, not all of the original magnetization could be recovered, and in fact, the amount of magnetization that could be recovered with successive cycles of the CP sequence was every time smaller and smaller; i.e., each echo was smaller than the one before. A line that would join the peaks from each echo was called the *echo envelope*. The echo envelope was a representation of portion of the magnetization that was due to the free state water present in the sample. Both the FID curve and the echo envelope were approximated by straight lines.

The total amount of magnetization, I_t , present in each sample was due to the water present in free state (physical water) and the water that had undergone hydration with the cement grains (chemical water). The fraction of the magnetization that was due to the physical water was labeled, I_p , and the fraction of the magnetization that was due to the chemical water was labeled, I_c . The functions that were used to approximate the FID decay and the echo envelope were labeled $F_{total}^{(t)}$ and $F_p^{(t)}$, respectively. I_t and I_p were obtained by extrapolating $F_{total}^{(t)}$ and $F_p^{(t)}$ back to their respective $t = 0$ values. I_c was obtained by subtracting I_p from I_t . The previous discussion is best illustrated in Figure 11.

In order to obtain the spin-spin relaxation time for the physical water, T_{2p} , it was necessary to normalize $F_p^{(t)}$ with respect to I_p . The normalized function resulting from this was labeled $f_p^{(t)}$. As reported by Jameson and Mason [10], the relaxation processes follow an exponential law depending on the excess number (n) of excited nuclei

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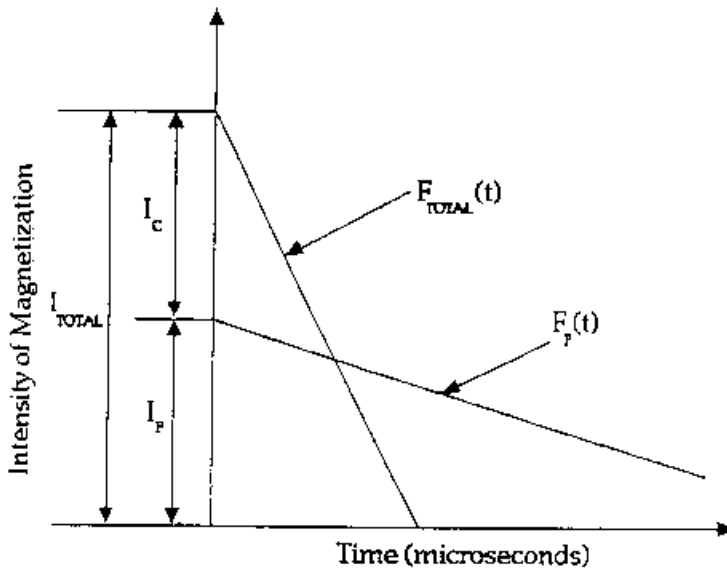


Figure 11 Functions for FID Decay and Echo Envelope.

compared to the number at equilibrium, so that the excess at time t after excitation is given by

$$n_t = n_0 \exp(-t/T) \quad (3)$$

where, n_t = energy excess at time t ; n_0 = energy excess at time zero; t = time after excitation; and T = relaxation time. T is a time constant characteristic of the system, such that the relaxation rate is T^{-1} . The spin-spin relaxation time (T_2) gives the rate at which the magnetization M_{xy} in the direction transverse to the applied field B_0 (xy -plane) returns to its equilibrium value after excitation. For simplicity, T_2 has been defined as the time lapse required for the energy excess to decrease by a factor of e (~ 2.7183). Consequently, T_{2p} was determined from a graph of the normalized function versus time as shown in Figure 12. As seen in Figure 13, the procedure for determining T_{2c} is identical to that for T_{2p} , except that the normalized function, $f_c^{(t)}$ is obtained by subtracting $F_p^{(t)}$ from $F_{total}^{(t)}$ and then normalizing the difference with respect to, I_c .

RESULTS

In this section, the results of NMR tests are discussed and correlated with the compression test results.

The variation of compressive strength, f'_c , of all compression cylinder tests with time is shown in Figure 14. The behavior is typical of that expected from curing concrete during its first 28 days.

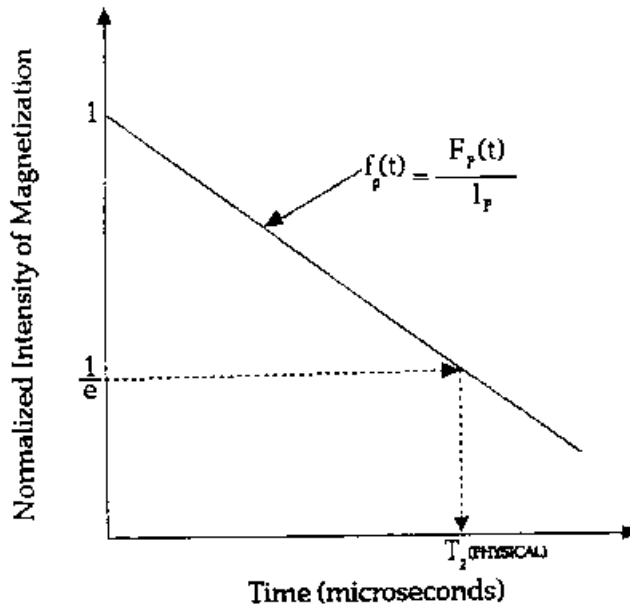
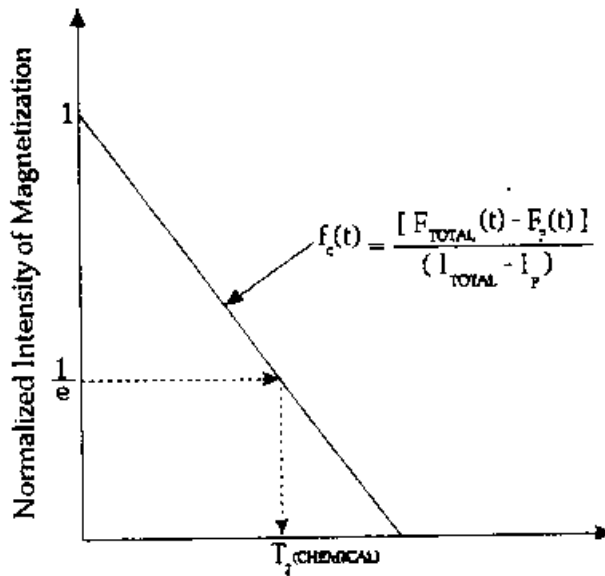
Figure 12 Graphical Method for Determining T_{2p} .Figure 13 Graphical Method for Determining T_{2c} .

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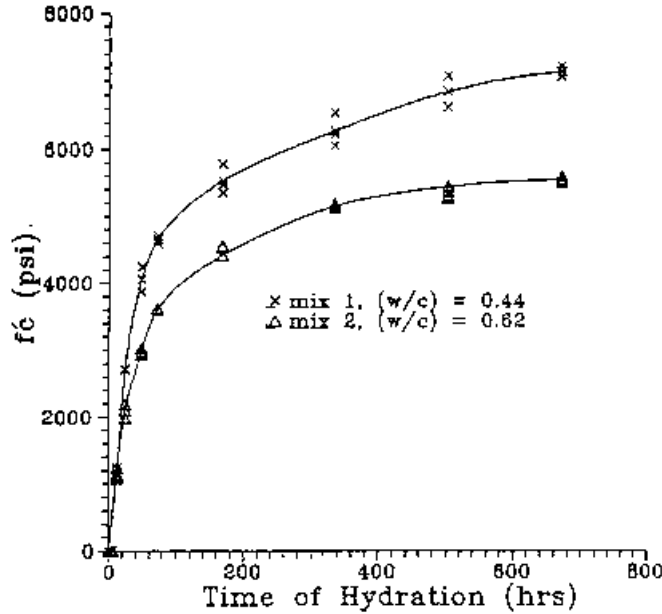


Figure 14 Variations of Compressive Strength of Concrete Cylinders with Time.

Figure 15 and 16 show the variation of percent of magnetization versus time for samples with W/C of 0.44 and 0.62, respectively. As can be seen from these figures, the behavior is almost bi-linear indicating a large amount of hydration activities during the initial times after casting. As the free water in the samples is consumed during hydration, its quantity (represented by percent of magnetization) is decreased. At the same time, the quantity of chemically bond water is increased. Since all kinds of evaporation was prevented, the sum of the physical (free) water and chemical (bond) water at each measurement is 100 percent indicating the total water content. It is interesting to compare the variation of compressive strength with time (Figure 14) to the plots shown in Figures 15 and 16. The fast rate of increase in the compressive strength during the initial hours is almost directly related to the fast increase in the percent of magnetization of the chemical water. This behavior has of course been verified by other techniques. However, its reconfirmation here points out to the suitability of NMR technique for studies related to the hydration behavior of concrete. Figure 16, showing the relationship for sample with W/C ratio of 0.62, indicates a flatter slope in latter part of the hydration as compared with that in Figure 15. This indicates that, due to the availability of more water, most of the hydration took place during the initial hours, i.e., the first 48 hours. Furthermore, at 28 days (last point on curve) the percentage of remaining free water is more than that for the sample with W/C ratio of 0.44 (Figure 15).

Figures 17 and 18 show the spin-spin relaxation times for free water, T_{2p} , versus time of hydration for samples with W/C ratio of 0.44 and 0.62, respectively. The behavior was almost an exponential decay for both W/C ratios. The relaxation times,

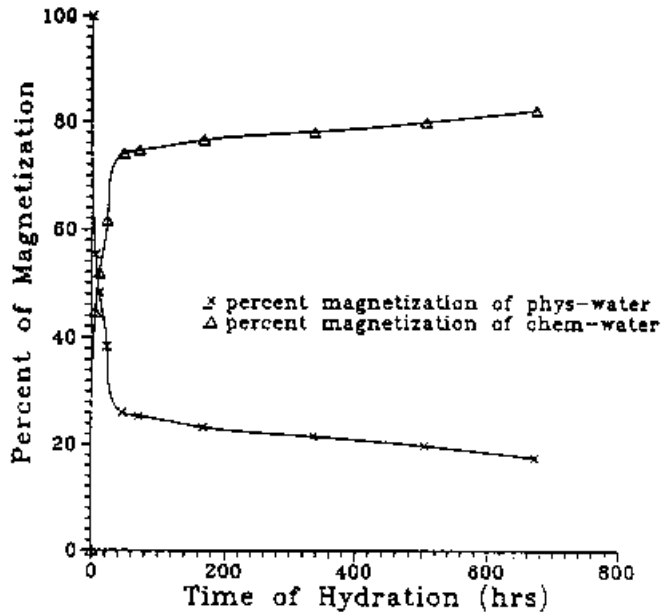


Figure 15 Variation of Percent of Magnetization with Time ($w/c = 0.44$).

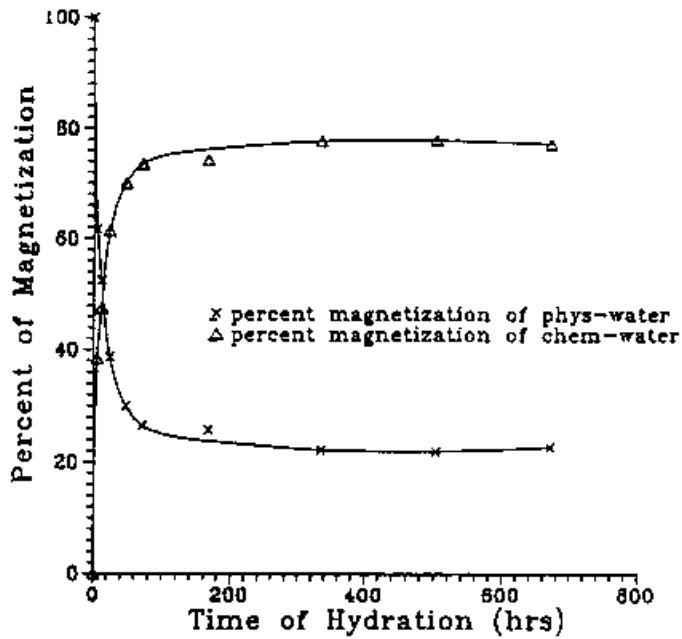


Figure 16 Variation of Percent of Magnetization with Time ($w/c = 0.62$).

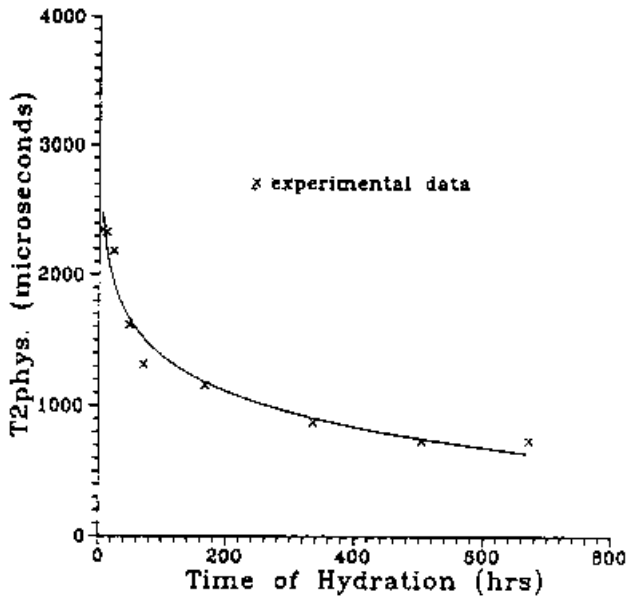


Figure 17 Variation of T_{2p} with Time ($w/c = 0.44$).

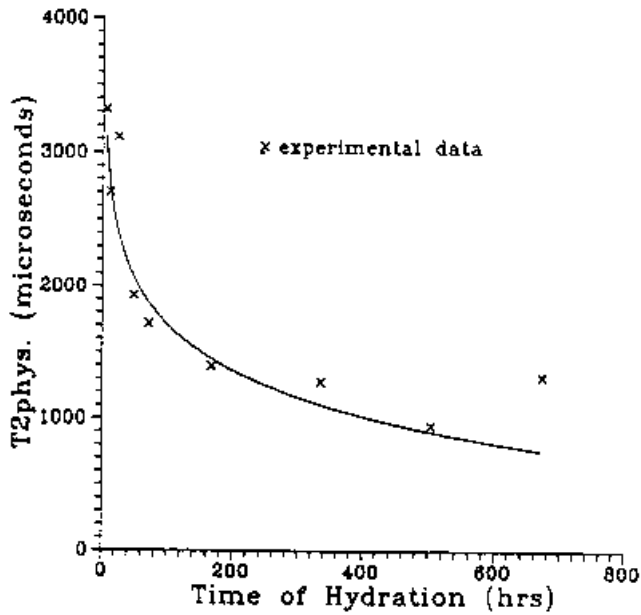


Figure 18 Variation of T_{2p} with Time ($w/c = 0.62$).

however, for the samples with W/C of 0.62, on the average, were larger than those with W/C of 0.44. For example, in Figure 17 (W/C = 0.44), T_{2p} , decreased from about 2600 μ seconds at 6 hours of hydration time to 700 μ seconds at 28 days. The corresponding, T_{2p} , values in Figure 18 (W/C = 0.62) are 3300 μ seconds and 1300 μ seconds, respectively. This is another indication of the sensitivity of NMR signals to the amount of water present or consumed during the hydration process in concrete.

As was indicated earlier, one of the objectives of the present study was to correlate the compressive strength of concrete to its pertinent NMR signals. Here an attempt is made to correlate the percent of magnetization of physical water, I_p , and the spin-spin relaxation time of physical (free) water, T_{2p} , to the compressive strength of concrete during the first 28 days of curing.

Figures 19 and 20 show the plots of I_p versus compressive strength during the first 28 days for samples with W/C of 0.44 and 0.62, respectively. The numbers shown next to the cross-marks on the figures represent the time in hours since casting. An almost linear relationship exists between the reduction in the amount of physical water and increase in compressive strength during the first 28 days of curing. Similar behavior is also observed in Figures 21 and 22 where the spin-spin relaxation

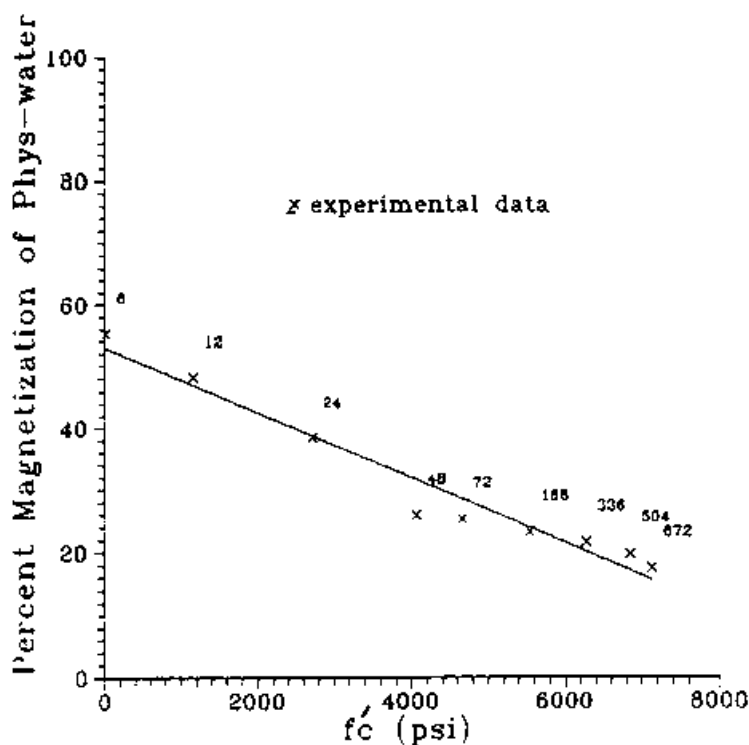


Figure 19 Percent Magnetization of Physical Water vs. Compressive Strength (w/c = 0.44).

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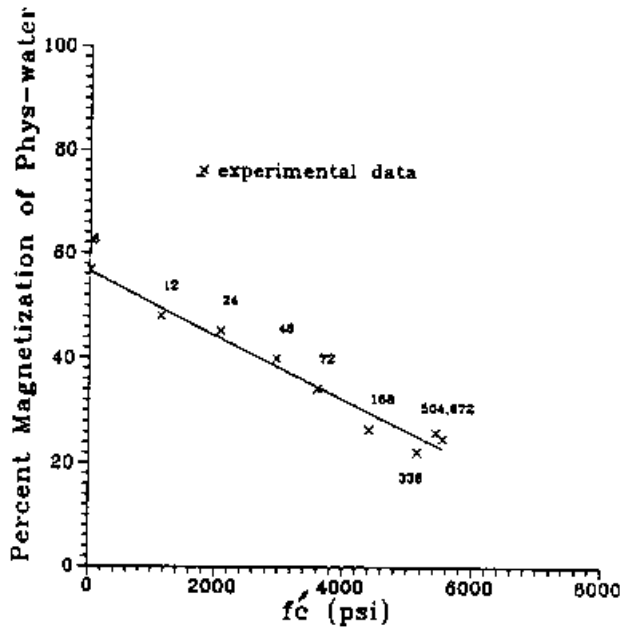


Figure 20 Percent Magnetization of Physical Water vs. Compressive Strength ($w/c = 0.62$).

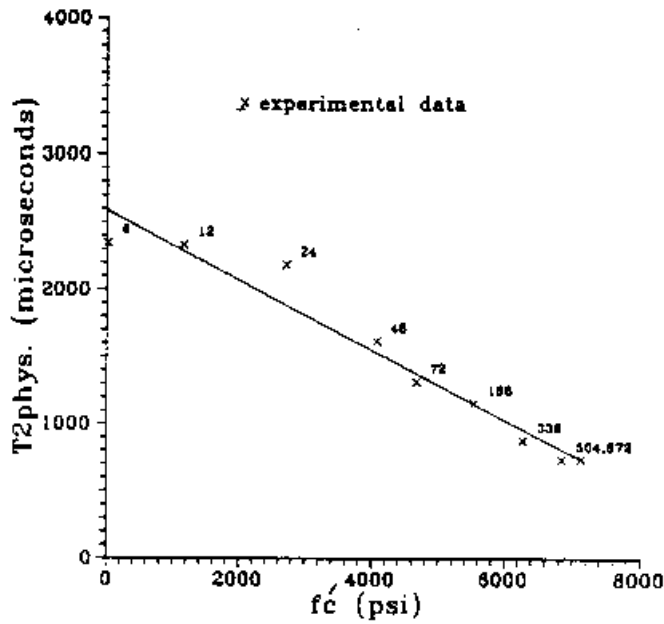


Figure 21 T_{2p} vs. Compressive Strength ($w/c = 0.44$).

and calibrate portable equipment for field evaluation of strength properties of concrete. Development of such equipment is feasible. In fact, the system used in this study was as big as a desk top computer. Before field application, however, the presence of reinforcing bars in concrete, and their effects on NMR signals, need to be investigated.

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References

1. General Electric, "NMR — A Perspective on Imaging." General Electric Company, Medical Systems Operations, 30 pages (1982).
2. J. W. Akkit, "NMR and Chemistry: An Introduction to Modern NMR Spectroscopy," Chapman and Hall Publications (1992).
3. J. McMurry, "Structure Determination: Nuclear Magnetic Resonance Spectroscopy," Organic Chemistry, Burkes/Cole Publishing Company, Second Edition, pp. 408–451 (1990).
4. R. K. Harris, "Nuclear Magnetic Resonance Spectroscopy," John Wiley and Sons, New York (1986).
5. R. Blinc, G. Lahajnar, S. Zumer and M. M. Pintar, "NMR Study of the Time Evolution of the Fractal Geometry of Cement Gels," *Physical Review B*, **28**(4), August 1, pp. 38–40 (1988).
6. L. J. Schreiner, J. C. MacTavish, L. Miljkovic, M. M. Pintar, R. Blinc and G. Lahajnar, "A Study of Portland Cement Hydration by Paramagnetic Ion Suppression of Proton Magnetic Resonance," *Cement and Concrete Research*, **40**, pp. 32–36 (1985).
7. J. C. MacTavish, L. Miljkovic, M. M. Pintar, R. Blinc, and G. Lahajnar, "Hydration of White Cement by Spin Grouping NMR," *Cement and Concrete Research*, **15**, pp. 367–377 (1985).
8. R. Rumm, H. Haranczyk, H. Peemoeller, and M. M. Pintar, "Proton Free Induction Decay Evolution During Hydration of White Synthetic Cement," *Cement and Concrete Research*, **21**, pp. 391–393 (1991).
9. D. D. Lassic, J. M. Corbett, J. Jian, J. C. MacTavish, M. M. Pintar, R. R. Blinc, and G. Lahajnar, "NMR Spin Grouping in Hydrating Cement at 200 MHz," *Cement and Concrete Research*, **18**, pp. 649–653 (1988).
10. C. J. Jameson, and J. Mason, "Multinuclear NMR," Plenum Press, First Edition, pp. 51–83 (1987).