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Experimental Study of Wave Propagation through Grouted Concrete

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The injection of cementitious grout into deteriorated civil structures is a common application for strengthening or repair purposes. The nondestructive estimation of the repair effect, which is always desirable, is not an easy task because geometry, constituent materials' property mismatch, and temperature-dependent hydration rate often impose difficulties to the characterization. In many cases, after the grout injection and the elimination of voids, the pulse velocity decreases unexpectedly, complicating the task of repair evaluation. In this work, an experimental study of stress wave propagation in concrete impregnated with injection cement is presented. It is revealed that, despite the common impression, wave velocity should not be expected to rise after repair in any case because the properties of grout are initially lower than the surrounding concrete. This effect can be emphasized by the low hardening rate that is imposed to the grout material in the case of low environmental temperature. The transmitted frequencies are also decreased shortly after injection and, therefore, the decrease of wave parameters such as velocity or amplitude should not necessarily be taken as a sign of unsuccessful repair or even deterioration.

Keywords: grouting; hydration; injection; nondestructive tests; porosity; temperature; ultrasonic testing.

INTRODUCTION

A common repair or strengthening technique used by civil engineers is the injection of a repair agent. The technique, known as grouting, is used for soil stabilization and strengthening in cases of oil well drilling,[1-3] tunnel excavation,[4] or filling the ducts of post-tensioning tendons.[5] It is also used in water intake facilities[6,7] for reducing leakage as well as enhancing structural integrity by eliminating the defects in deteriorated structures.[8-10] In the case of strengthening massive deteriorated concrete elements—for example, dam piers—the repair agent is injected into boreholes drilled on the structure's surface to penetrate into the interconnected network of cracks and voids and eliminate them. Therefore, the repair agent becomes a part of the structure and, as such, its properties are of extreme significance. Specifically, the important parameters are the flowability and setting and hardening time when fresh, as well as compressive and shear strength and elastic modulus of the hardened state.[4,11,12]

The established ways for estimating the grouting efficiency are pullout tests or core extraction, which are destructive if under certain conditions they affect the mechanical properties of the structure, and are time-consuming and expensive.[11] Therefore, it is desirable to assess the grouting quality in a noninvasive way, and the application of stress waves has been researched.[7,11,13,14] It is assumed that filling the voids of the material with cementitious grout would increase the wave velocity and, therefore, an estimation of the grouting process would be straightforward. Although the cases are not similar, this trend has been observed in cement-based materials with water-saturated pores. They exhibit higher velocities than dry pores at frequencies above 500 kHz.[15] The reason should be the higher velocity of water compared with the air, but the additional stiffness provided by the material (water in this case) that fills the empty porous space is also considered.[15] The simultaneous increase of the effective density, however, should also be important, as well as the frequency used for the test, that can substantially influence the propagation behavior of inhomogeneous material such as concrete.[16,17] As will be discussed in the following, for the low frequencies applied in-place after grouting of a concrete structure, a velocity increase should not always be expected because other parameters such as the temperature, the age of grout at the time of the test, as well as the condition of the concrete matrix material contribute to the wave behavior.

The motivation of this experimental work originates from the repair project of a water intake facility in a cold area of Japan. After pulse velocity and acoustic emission monitoring, certain areas of troublesome integrity within the dam piers were detected (details about the entire monitoring and repairing procedure can be found in Reference 7). The selected repair procedure involved injection of a repair agent into the structure by boreholes drilled on the surface. Two weeks after the repair, a second stress wave monitoring took place. Unexpectedly, the velocity measurements through all sections of the structure that were examined did not reveal an increase of velocity but, instead, a general decrease of the order of 5%.[7,18] Even this small reduction deserved attention due to the importance of the structure, especially because the repair had been conducted. The reason for this behavior was not obvious because, according to the common impression, even if the defects were not completely eliminated by grouting, this was still not expected to negatively influence the propagation velocity or the structural integrity itself. Therefore, the need to clarify if such a trend is normal or not led to the present experimental study.

Specifically, concrete specimens impregnated with injection cement were ultrasonically examined at different ages to estimate the effect of grouting in an actual structure. In any case, a clear decrease in velocity was observed immediately after injection, especially for low temperatures. In addition, there was an immediate downshift of transmitted frequencies that explains the increased attenuation exhibited after the repair of the actual massive concrete structure. The findings suggest that a decrease of pulse velocity and transmission in an actual structure after repair with cement injection is normal and could be emphasized by low temperature.

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RESEARCH SIGNIFICANCE

The application of elastic waves is, in most cases, the only noninvasive method for assessing filling conditions after repair with injection cement. Elevation of velocity after repair would generally imply that the voids have been sufficiently eliminated. According to the authors' experience concerning grouting, especially in cold environments, however, the measured velocity decreases after repair. This phenomenon has been stated previously[14] but no sufficient explanation was given. In the present paper, a series of ultrasonic measurements in grout-impregnated concrete specimens reveals the effect of temperature and age, suggesting that even a decrease in wave velocity should not be mistaken as a sign of deterioration.

EXPERIMENTAL PROCEDURE

Materials

To examine the effect of grouting on the pulse velocity of concrete, three concrete specimens were impregnated with grout. In typical cases of repair, the volume of injected grout accounts for less than 1% of the volume of the structure. In this investigation, however, high-porosity concrete specimens were selected for the injection. This is due to the large empty volume (approximately 35%, measured by ASTM C642) that can be filled with grout and lead to highlighted effects, easy to be studied. Additionally, the size of the crushed stone aggregate (13 to 20 mm [0.51 to 0.79 in.]) resulted in large-scale porosity, easy to be impregnated. The specimens were cylindrical with a diameter of 100 mm (3.94 in.) and a length of 200 mm (7.87 in.). More details about the mixture proportions of the porous specimens, as well as their initial pulse velocities, can be found in Table 1. The paste-to-gravel ratio by weight was 0.25, whereas, as can be seen in Table 1, the porosity of all the specimens was approximately the same level. One specimen (Specimen L) contained lightweight aggregates and its pulse velocity was much lower than the normalweight specimens, N1 and N2.

Table 1—Properties of porous specimens

Specimen*	Porosity, %	Aggregate density, kg/m^3 (lb/ft^3)	Overall density, kg/m^3 (lb/ft^3)	Pulse velocity, m/s (ft/s)
N1	34.48	2674 (166.9)	1641 (102.4)	4545 (14,911)
N2	35.34	2674 (166.9)	1646 (102.8)	4301 (14,111)
L	36.30	1080 (67.4)	834 (52.1)	2713 (8901)

*w/c by mass of all specimens was 0.3 and paste-to-gravel ratio was 0.25.

Table 2—Basic chemical ingredients of injection cement

Ingredient	Percent by weight
SiO_2	26.4
Al_2O_3	13.0
Fe_2O_3	1.2
CaO	47.4
MgO	3.8

The type and water-cement ratio (w/c) of the grout used to impregnate the specimens were the same as used in the repair of the actual concrete dam. Specifically, the material was quick setting and hardening injection cement made primarily of blast furnace slag. The sulfate content was 1.4%. The chemical composition can be seen in Table 2. The density was 2980 kg/m^3 (186.03 lb/ft^3) and the average particle size was 3.1 μm (122 × 10^{-6} in.). The w/c by mass applied for casting of the grout was w/c = 1. According to the manufacturer, at the age of 28 days, the grout obtains a strength of 25 MPa (3.625 ksi). After mixing, the density of the grout was 1498 kg/m^3 (93.52 lb/ft^3).

The porous concrete specimens were impregnated with this grout in a vacuum chamber. Specimens N2 and L were maintained at a temperature of 20 °C (68 °F) and one was placed in an environmental chamber at 5 °C (41 °F) to check the temperature effect. This temperature was nominally the same with the concrete dam site. At that time of year, when the actual repair took place, the average temperature was below 0 °C (32 °F). To improve hydration according to JSCE Guidelines,[19] jet heaters elevated the surface temperature of concrete to 5 °C (41 °F). Therefore, Specimen N1 was maintained at this temperature to simulate the real conditions of grout hydration at the site.

Additionally, two prism specimens of plain grouting material with w/c = 1 by mass and dimensions of 400 x 100 x 100 mm (15.75 x 3.94 x 3.94 in.) were cast in steel forms to examine the properties of the grout material separately. The molds were removed 24 hours after mixing, and thereafter the specimens were cured at 5 °C (41 °F).

Stress wave measurements

The ultrasonic setup is a simple through-transmission configuration and, therefore, only a brief description will take place herein; more experimental details can be found in another study.[18] A high-energy pulse generator system was used along with its transducer with an output voltage of 1000 V. The frequency of excitation was approximately 50 kHz and the wave path through the porous specimens was 200 mm (7.87 in.). As a receiver, an acoustic emission sensor was used and the signals were acquired. A layer of grease was applied between the concrete surface and the sensors to enhance acoustical coupling. The ultrasonic setup can be seen in Fig. 1. For the plain grout, measurements were conducted perpendicular to the longitudinal axis of the prism specimens at a wave path of 100 mm (3.94 in.). Additional measurements were conducted on the surface of these specimens for the determination of the Rayleigh wave

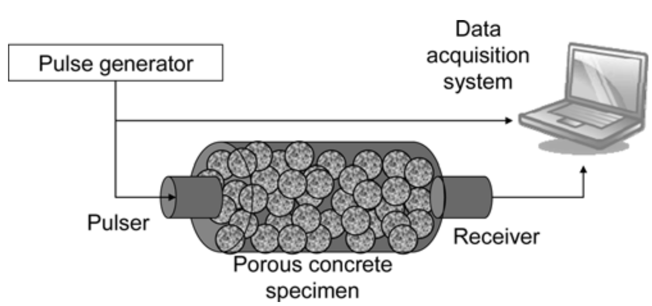

Fig. 1—Experimental setup for porous concrete pulse velocity measurement.

velocity. Measurements were conducted from the first day up to approximately 3 months.

RESULTS AND DISCUSSION

Injection cement specimens

As stated previously, measurements were conducted on pure injection cement specimens as well as porous concrete specimens impregnated with this injection cement. Results of the pure specimens will be presented first. In Fig. 2(a) the longitudinal velocity measured in through-transmission mode (wavepath 100 mm [3.94 in.]), as well as the Rayleigh velocity measured on the specimens' surface, are depicted versus the age of grout. The trends, which are normal for cementitious materials,[20,21] show an initial rapid increase up to approximately 10 days, whereas afterward, the velocities seem to converge to 3500 m/s (11483 ft/s) for longitudinal velocity and 1750 m/s (5741 ft/s) for Rayleigh velocity. Using the velocity values for any age, the Poisson's ratio ν can be calculated by the well-known elasticity relation[22]

$$C_P = \frac{1+\nu}{0.87+1.12\nu}\sqrt{\frac{2(1-\nu)}{(1-2\nu)}}C_R \tag{1}$$

where C_P and C_R are the longitudinal and Rayleigh wave velocities, respectively.

The results are depicted in Fig. 2(b). The value for Poisson's ratio was initially 0.4 when the material was fresh and approaches 0.28 at later ages. The aforementioned results imply that the material used for impregnation exhibits a typical behavior because it follows the well-known trend of velocity increase with age. When this homogeneous material is injected in concrete, however, the behavior of the composite system becomes highly complicated, as will be seen in the next section.

Impregnated porous concrete

Measurements on the porous concrete took place before and at several ages after impregnation with grout. The results of the examination are depicted in Fig. 3 for all specimens. On the vertical axis (age 0 days), the velocity values before impregnation can be seen. One day after the impregnation, a decrease of pulse velocity from 5 to 13% was noticed for all specimens. It is interesting to compare the behavior of normalweight Specimens N1 and N2. As seen in Fig. 3(a), although Specimen N1 exhibited higher initial velocity, this trend was reversed eventually after impregnation. The pulse velocity of this specimen never recovered, being just above 4000 m/s (13,123 ft/s) or approximately 10% lower than the initial value, even at the age of 3-1/2 months. Concerning Specimen N2, the velocity at 3 months was restored to a level similar to that before impregnation. This different trend between the two specimens is most likely connected to the temperature because Specimen N1 was maintained at 5 °C (41 °F), whereas Specimen N2 was maintained at 20 °C (68 °F)—a difference that substantially affects the hydration rate of grout. In any case, none of the specimens exhibited an increase of velocity even at later ages, and this is related to the mismatch of the properties of grout and concrete.

Specifically taking into account the initial velocities of Specimens N1 and N2; the effective densities of Table 1; and considering a Poisson's ratio of 0.2, which is typical for these materials, an approximate value for the dynamic elastic modulus of both specimens is calculated at approximately 30 GPa (4351 ksi) through Eq. (2)

$$C_P = \sqrt{\frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}} \tag{2}$$

where E is the dynamic modulus of elasticity, ρ is the density, ν is the Poisson's ratio, and C_P is the longitudinal wave velocity.

On the other hand, using the values of pulse velocity and Poisson's ratio for plain grout that are presented in Fig. 2,

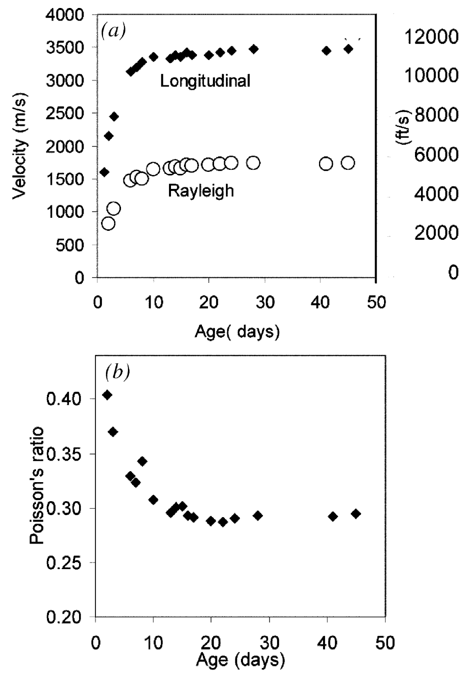

Fig. 2—Development of: (a) wave velocity; and (b) Poisson's ratio of grout with age.

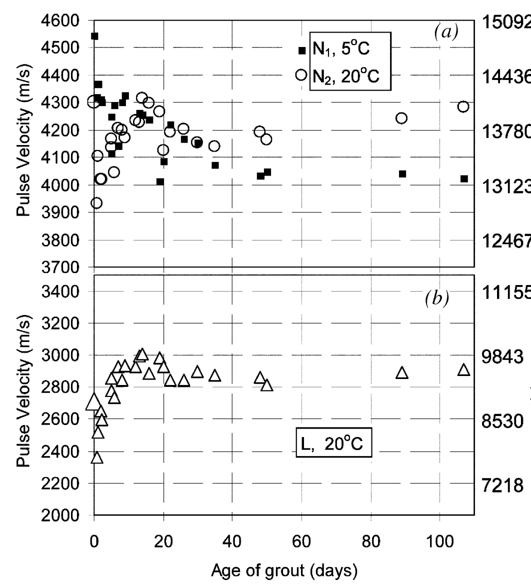

Fig. 3—Pulse velocity of porous concrete specimens before and at different ages after impregnation with grout: (a) normalweight aggregates; and (b) lightweight aggregates. (Note: 1 °C = 33.8 °F.)

according to Eq. (2), the dynamic elastic modulus of grout is estimated at approximately 3 GPa (435 ksi) at 2 days and developed to approximately 15 GPa (2176 ksi) after 1 month. Therefore, in such a case, although the voids are filled with grout, this cementitious material is too soft compared with the matrix to lead to an increase of pulse velocity.

In the actual case of a grouted structure such as a dam, injection of grout has the positive effect of decreasing the permeability as well as increasing the load-bearing cross section. Because the material injected is of much lower elasticity than the matrix, however, the pulse velocity should not be expected to automatically rise.

On the contrary, the lightweight Specimen L (refer to Fig. 3(b)) exhibited a quick recovery after the early decrease. Five days after impregnation, its velocity rose over the initial level of 2700 m/s (8858 ft/s) and remained at a value of approximately 6.6% higher until the last measurement at 3.5 months (2892 m/s [9488 ft/s]). Using the initial pulse velocity of Specimen L, the effective elasticity modulus can be estimated at approximately 6 GPa (870 ksi) using Eq. (2). Therefore, the fresh grout that initially had inferior properties (3 GPa [435 ksi] as mentioned previously) lowers the velocity. Rather quickly, however, it obtains elasticity similar to or superior to the matrix (9 GPa [1305 ksi] at the age of 6 days and 15 GPa [2176 ksi] at 1 month, as mentioned previously) and the measured velocity for the entire composite is increased above the initial level of the porous concrete.

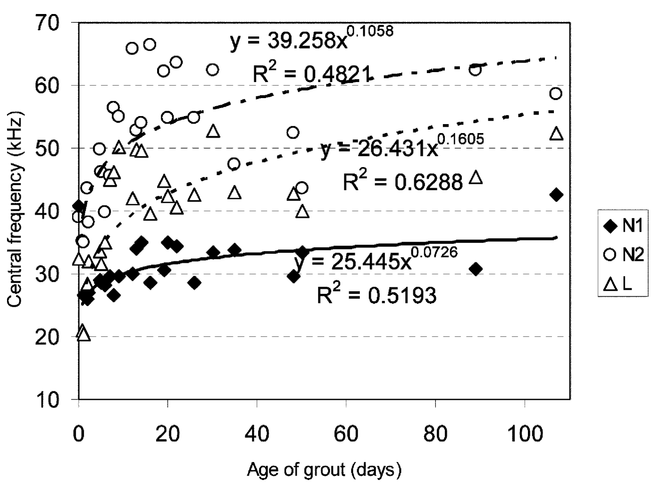

Fig. 4—Central frequency of waveforms of porous concrete specimens before and at different ages after impregnation with grout.

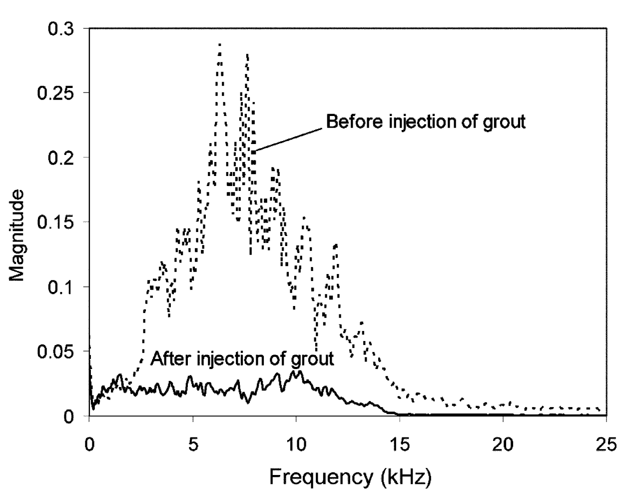

Fig. 5—Typical FFTs of signals recorded at actual structure.

The conclusions are similar if the time-dependent acoustic impedance of the constituent materials is considered. According to the listed values of velocity and density in Table 1, the acoustic impedance value for grout is initially 2.25 MRayl and reaches 5.25 MRayl at later ages. For normalweight porous concrete, the impedance is approximately 7 MRayl and for the lightweight porous concrete, the impedance is approximately 2.25 MRayl. It should be mentioned, however, that the overall density of the porous concrete is low due to the air occupying more than 30% of the volume. The mismatch of interest in this case is between the grout material and the aggregates of the porous concrete that occupy almost the entire remaining volume of the porous concrete specimens. The impedance of the normal aggregates is more than 11 MRayl and the impedance of the lightweight aggregates is approximately 3 MRayl. It is seen that the normalweight aggregates always have higher impedance than the grout. The situation is different for the lightweight aggregates; initially they exhibit similar or somehow higher impedance, but later the hardened grout stiffens and the impedance increases over the porous lightweight matrix. Thus, the wave velocity of this specimen is quickly increased.

It was mentioned that the stiffness of the inclusions does not always dictate the behavior of the measured velocity of the composite according to what is generally expected. It has been observed that impregnation of cementitious material into a porous matrix decreases the velocity at some cases[7,14] as already discussed. On the other hand, stiff inclusions in a softer matrix (for example, iron in polymer) decrease the velocity of the composite at low frequencies.[23,24]

The aforementioned demonstrate the influence of temperature as well as the properties' mismatch in the velocity response of grouted concrete. In case the surrounding matrix has much higher mechanical properties than the grouting material, the overall velocity will reduce permanently (such as in the case of Specimen N1) or at least for a period of time until the grout sufficiently hardens (such as in the case of Specimen N2). In case the matrix material has low elastic constants (for example, due to the initial mixture design [such as in the case of Specimen L] or possibly severe deterioration in case of an old structure, however, grouting will have a positive impact on velocity more quickly. In such a case, this is because even the incompletely hydrated grout of a few days is stiff enough compared with the matrix. This can be explained similarly to the soil grouting. Soil is characterized by low mechanical properties, and therefore almost immediately after grouting, measurements exhibit a velocity increase,[25] which of course becomes more evident at later ages.

Frequency transmission

Similar trends hold for the transmitted frequencies. Generally, it is expected that any inhomogeneity responsible for pulse velocity changes should have an even more pronounced impact on energy-related parameters.[26] As stated previously, the central excitation frequency of the high voltage pulser is approximately 50 kHz. The initial measurements, before impregnation, revealed clearly lower central frequency for all porous specimens (refer to points on the vertical axis of Fig. 4) for the age of 0 days. Specifically, the central frequencies were approximately 40 kHz for normalweight Specimens N1 and N2 and 32 kHz for lightweight Specimen L. This decrease compared with the excitation is reasonable due to the severe scattering imposed by the inhomogeneous structure of the porous material.

A further decrease of frequency content was observed immediately after impregnation for all specimens, despite the fact that the porosity was eliminated by cementitious material, as was noticed earlier for pulse velocity. The hydration process, however, gradually increased the elastic modulus of grout. This should be the reason for the frequency increase that was subsequently measured for all specimens, as seen in Fig. 4. The increase was more rapid for the lightweight Specimen L, as revealed by the higher exponent of the fitted equation, whereas the normalweight Specimen N1, maintained at 5 °C (41 °F), exhibited the slowest increasing rate and never transmitted frequencies as high as before impregnation. The fitting was conducted by standard functions of computer software. The transmitted frequencies for this specimen seemed to converge with age at approximately 35 kHz, whereas the central frequency before impregnation was 41 kHz. This again shows that grouting in cold environments has a nearly-permanent effect on the frequencies transmitted, as was also the case for the pulse velocity. It is noted that the experimental scatter observed in Fig. 3 and 4 is due to the rough surface of the porous concrete, making the acquisition of absolutely repeatable measurements difficult. Therefore, each point comes from the average of three individual measurements.

The injection of grout had a strong effect on the transmitted frequencies in the actual case of the dam site as well. In Fig. 5, one can observe the fast Fourier transform (FFT) of typical responses through the 2.2 m (7.22 ft) thickness of a concrete pier excited by impact hammer[7] before and 2 weeks after injection of the repair agent. It is obvious that the grouting has a definite influence on the frequency spectrum. The transmitted energy clearly diminished, while only the first 2 kHz seem to be unaffected. Concentrating on the first 25 kHz, the central frequency decreased from 9 kHz to 7.5 kHz two weeks after repair. This trend is similar to the case of porous concrete Specimen N1, impregnated at 5 °C (41 °F) in the laboratory, for which the central frequency suffered a downshift from 40 kHz to less than 30 kHz two weeks after grout injection. In the actual dam, the frequencies are much lower than in the laboratory, something reasonable due to the different excitation method as well as to the longer propagation path. In the specific examples of Fig. 5, the signals were collected 2.2 m (7.22 ft) away from the low-frequency impact excitation, in contrast to the 200 mm (7.87 in.) of the grouted porous specimens using the 50 kHz pulser.

These findings demonstrate the influence of fresh grout injection on wave propagation in concrete showing that a decrease in transmitted frequencies is to be expected in an actual situation for at least some time period after repair with grouting.

It is also reminded that, due to difference in temperature, the maturity of grout is expected to differ in the specimens. The effect on strength, however, is expected to be very limited after an age of 3 months for the specific temperatures (5 and 20 °C [41 and 68 °F]).[27] Therefore, an extensive study of this parameter was not conducted because the authors intended to deal mainly with the wave propagation behavior and explain the reason for the initial velocity decrease. Furthermore, maturity is used to estimate the developed strength, and the use of this concept to explain the wave propagation behavior would not be reliable.

CONCLUSION

The present experimental study aims to improve the understanding of wave propagation in concrete structures injected with grouting material. So far, it is expected that filling the empty space of cracks or voids in a concrete structure with cementitious material would, in any case, lead to an increase of pulse velocity and wave amplitude and, therefore, the repair assessment would be straightforward. However, this is not always observed in actual conditions. Furthermore, the findings of this experimental series demonstrate that, due to the initially low elasticity of fresh grout, a decrease is the most likely case, despite the improvement of the structure in terms of permeability and load-bearing capacity.

Specifically, apart from the injection cement properties, two other parameters seem significant for the wave behavior of the entire structure. These are:

1. The temperature that influences the hardening rate of grout and, therefore, its mechanical properties at a given age. Low temperature during grouting will lead to lower velocity for a long period of time or even permanently; and

2. The condition of the structure to be injected. In a case that the matrix concrete is stiff enough (not deteriorated), it is likely that its mechanical properties will be much higher than the injected grout. Therefore, an increase of pulse velocity should not be expected even if voids are successfully eliminated. In the opposite case, if the matrix is severely deteriorated and the material properties are low, an increase of pulse velocity and frequencies transmitted could be evident shortly after the repair.

Due to the aforementioned parameters, the influence of grouting in velocity cannot be known beforehand. It is reasonable to assume, however, that the small velocity change should be related to small void volume filled. In case the grouting is extensive and a large volume of voids is eliminated, a large velocity decrease should be expected initially.

The aforementioned experimental results are currently theoretically investigated using scattering theory[28] because strong scattering mechanisms are certainly active in such a material, even at low frequencies. Another possible approach is the application of homogenization models[29,30] for the estimation of the effective physical properties of the composite material because the injection of grout increases both the total elasticity modulus as well as the density of concrete and, therefore, has an ambiguous effect on pulse velocity.

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