NDT Non-Destructive Test for Quality Evaluation of Concrete specimens by Ultrasonic Pulse Velocity measurement

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Abstract. Knowing the quality of concrete is very important, because this type of material is part of the design and implementation of most structures such as bridges, buildings, tunnels, among others, in this investigation non-destructive tests were carried out on test specimens of using ultrasound, which were designed and developed in the concrete laboratory at Santo Tomas University in Bogotá D.C. taking into account for its preparation a dosage of the estimated concrete mixture in order to obtain specimens with a compressive strength of 3500psi, 2500psi and 1500psi, in such a way, the specimens were allowed to cure for a period of 28 days, ensuring that they achieved their maximum compression strength. As mentioned above, non-destructive ultrasound tests were applied in order to determine the quality of the manufactured concrete specimens, thus, an ultrasound system is proposed that makes it possible to pass an acoustic wave through a concrete specimen, this was proposed with the purpose of measuring the velocity with which the wave passes in the volume of this material, known as the ultrasonic pulse velocity. Therefore, the respective velocities for each of the concrete specimens were measured, thus finding a relationship between the ultrasonic pulse velocity and the compressive strength, which finally makes possible the evaluation of the manufactured concrete specimens.

1. Introduction

In the construction area, concrete acts as a main material when developing any type of structure, this is because it provides security, stability and is comfortable to work being adapted to any means, taking advantage of its malleability characteristic. For the realization of the mixture that composes the concrete materials that are easy to obtain are used because they are extracted from nature, among these materials is sand, gravel and water. The dosage of them has an important role, such that the amount of each component used in the mixture directly affects the final strength of the concrete.

To evaluate the quality of the concrete, the compressive strength is usually measured in a machine with hydraulic press, so that the press compresses the concrete to its breaking point, thus determining the strength of the concrete according to the applied force, however, at present there are other non-invasive methods, such as non-destructive tests by means of ultrasound, which allow to estimate the concrete strength without having to alter its condition or the properties it possesses, this is achieved by measuring the ultrasonic pulse velocity with which an acoustic wave travels through the concrete specimen.
Therefore, it is decided to manufacture concrete specimens with specific characteristics and therefore measure the ultrasonic pulse velocity with the help of ultrasound equipment available in the laboratories of the Santo Tomás University. In this way, the methodology shown in figure (1) is proposed and implemented, which is composed of three stages, in the first instance, the design of the concrete specimens, in the second instance the preparation of the same, taking into account as a design criterion, three different strengths, 3,500 psi, 2,500 psi and 1,500 psi, lastly, the measurement of the ultrasonic pulse velocity at each of the concrete specimens.

![Figure 1. Methodology used.](image)

2. Concrete

Concrete is the most useful material in structures such as retaining walls, bridges, foundations, columns, beams, among others, since it is economical, easy to melt, durable and resistant to the moment of setting, that is, when the material passes from a plastic state to a solid state.

Concrete is made of cement, a fine aggregate such as sand, a coarse aggregate such as gravel, water and, if necessary, additives are added. In figure (2), the proportion of the components within the concrete mixture [1], which form a manipulable paste, uniform due to the chemical reaction of the water with the cement, to form part of the solid body can be seen of concrete [2] and with excellent compressive strength when the concrete is hardened, that is, the ability of the material to withstand a flattening load. It is also important to highlight that the concrete has some weaknesses such as low tensile or tensile strength, this property refers to the ability of the material to oppose being elongated by forces in different directions.

Hydraulic cement is a finely ground powder, which is produced by burning limestone together with clay in an oven, at a temperature of 1,450 C [3], the union between these two elements is known as a clinker, which It is mainly composed of calcium silicates and, to a lesser extent, calcium aluminates, which, mixed with water, combines, sets and hardens at room temperature, both in air and underwater [4]. In turn, the cement is a conglomerate, that is, a material capable of joining elements and that when hydrated with good quality water it is transformed into a paste or dough [4], so that it obtains stiffness and strength over time, which is mostly acquired by the cement used in the concrete, which is why the greater the amount of cement content in the concrete, the greater the strength, however, in order to achieve an adequate and effective concrete, it is necessary to use of a single type of cement, since if several types are used in a single mixture, the components and characteristics of each one can alter the results that are desired [5].

To reduce costs and contribute to the concrete strength, a large percentage of aggregates that are clean of waste are used, which contribute significantly to the volume in the concrete mixture. This material is originated by igneous, sedimentary and metamorphic rocks, either by crushing or disintegrating them [6], which are classified into two groups such as the thin ones, where the sand and the coarse ones such as gravel, these are named as such because of the difference in size they have.

Due to the texture of the particles, they make up the rigid concrete body when it is in the fresh state, which when mixed adhere to the other elements being completely covered by the cement paste with water, this satisfies the results of hardened concrete and also providing smooth surfaces, suitable for developing different tests [7]. Within the characteristics that the aggregates possess, granulometry is important since it determines the sieve, that is, the size of the particles in which the sand must be found,
is classified as having a minimum particle size of 0.075 mm and a maximum of 4.76 mm, in turn, the gravel is classified into a minimum particle size of 4.76 mm and maximum of 75 mm.

Finally, in the large environment of the constriction there is a wide variety of additives either in liquid or powder form, which are incorporated in small parts either before or while preparing the mixture [8], that is, in the fresh state in order to improve the original condition of the concrete, this occurs due to the various characteristics and reactions that the use of each additive possesses, taking into account the function that is required such as accelerating or retarding the setting, reducing water, accelerate strength, among others. The above is used to improve strength, avoid failures and improve conditions to work better concrete.

**Figure 2.** Percentage of the volume occupied by each material in a concrete mixture.

### 3. Measurement of the ultrasonic pulse velocity in concrete specimens.

Among the specific techniques to perform non-destructive tests on concrete, those that use ultrasound are included, these are used to determine the quality of concrete strength, without altering its physical properties, therefore, the use of these techniques helps to determine the state of the structures made with said material.

The measurement of the ultrasonic pulse velocity in concrete structures is based on the measurement of the return time it takes for an ultrasound wave to travel through a concrete volume. For this measurement one of the most used methods is the direct method, where the transducers are located on the opposite surfaces of a concrete specimen, in this case cylindrical as shown in figure (3). For the correct implementation of the method, sufficient acoustic coupler must be used on the joint surfaces between the transducers and the concrete, the above, in order that the acoustic impedance present due to the change of medium decreases and allows the acoustic wave to travel through concrete without reflecting.
In order to generate an acoustic wave and measure your flight time in passing through the test specimen of concrete, it makes use of an ultrasound system like the one that can be seen in figure (3), it is composed of a Ultrasonic pulse generator, which is responsible for exciting an ultrasonic transmitter transducer (Tx), which generates pressure waves that travel through the concrete, this generated signal can be seen through an oscilloscope. The transducer receiver (Rx) picks up the acoustic wave when it reaches the end of the specimen, and fulfils the function of generating an electrical signal corresponding to the received ultrasonic wave, this electrical signal is shown in an oscilloscope. Therefore, by synchronizing the oscilloscope channels, the time between the pulse and the received signal can be evidenced, this time corresponding to the flight time (t) of the acoustic wave through the distance (d) of the concrete specimen, in such a way that given the length of the specimen and the flight time, the ultrasonic pulse velocity in the concrete is determined, as shown by the expression in equation (1).

\[ V = \frac{d}{t} \]  

(1)

4. Design and development of concrete specimens.
As discussed above, are designed and produced concrete test specimens of three different strength, which are 3500psi, 2500psi and 1500psi as can be evidenced in figure (4), in order to verify and have a greater accuracy of the ultrasonic pulse velocity, two specimens are made for each strength since it is established that it is the minimum number of specimens to be tested.
For the composition of the concrete, the elements used were the following: First, cement as the main element to acquire strength; which for the present case was used the gray cement type one of Argos, this is the one of general or normal use [8] and is used in any structure or civil works.

On the other hand, in the mixture, arid elements such as sand and gravel were used; where the gravel has a density of 1500 kg/m³ and a particle size of 3/4", This material, to ensure excellent quality, it must be clean of any fine like clay, well graded and with a rough texture, because if the material is round, elongated and smooth [7], it affects the strength that want to acquire. Likewise, the sand used in the mixture is that obtained from the river, because it is of high quality and is often used in the concrete mixture, especially because of its high quartz content [6]. This type of sand is characterized by a density of 1450 kg/m³, and in order to be used in construction it must meet certain conditions as well as gravel, since both must have high durability and be clean, without having a coating of other materials, which interfere with the adequate hydration of the particles.

Finally, to the elements mentioned above, the necessary amount of water must be added, in order to form the concrete mixture; because water is the essential component that is responsible for the cementation process, on the one hand, it hydrates the cement molecules, transforms the physical and mechanical properties of this material and also providing malleability and the fluidity necessary for the development of the concrete that you want to perform. It is important to keep in mind that the water that must be used to obtain a quality concrete, must be that which is also suitable for human consumption, that is, it must not have other substances such as: oils, acids, garbage, matter organic or other fluids that alter its properties or molecular structure [7].

However, in order to acquire the desired strength, an excellent dosage is needed, that is, the necessary quantity of each previously named material, which must contain the concrete mixture, this quantity must be appropriate to provide an easy working mixture and economical. From the water content, the water / cement ratio and volume of the aggregates [11], the dosage for a concrete specimen can be obtained, however, table (1) presents an accepted dosage example for a volume of 1 m³.

| Resistance (psi) | cement (Kg) | Sand (m³) | Gravel (m³) | Water (l) |
|------------------|-------------|-----------|-------------|-----------|
| 3500             | 420         | 0,67      | 0,67        | 220       |
| 2500             | 300         | 0,48      | 0,96        | 170       |
| 1500             | 210         | 0,5       | 1,0         | 160       |

According to the specifications of the materials, and according to the quantity required by each of these, the value of the dosage is calculated on the basis of the data found in the table (1) for the volume of the concrete specimen (Vp) of 0.0053 m³, as shown in the table (2); this value corresponds to the dimensions of the specimen pieces of 0.15m diameter (D) by 0.30m height (h). Considering the above situation, for to obtain the volume was determined using the expression in the equation [2].

\[ Vp = \frac{\pi}{4} \times D^2 \times h \]  

(2)

Table 2. Dosage of concrete for one volume 0,0053m³

| Resistance (psi) | cement (Kg) | Sand (m³) | Gravel (m³) | Water (l) |
|------------------|-------------|-----------|-------------|-----------|
| 3500             | 2,226       | 0,003551  | 0,003551    | 1,166     |
| 2500             | 1,59        | 0,002544  | 0,002544    | 0,901     |
| 1500             | 1,113       | 0,00265   | 0,00265     | 0,848     |

When determining the correct volume that is required for a concrete specimen, proceeds to convert the amount of sand and gravel into kilograms, this is done in order to facilitate the work of measuring
each of the materials in the mixture, for this, using the expression in equation (3), the data of the mass variable \( m \) is obtained, because the known data are the densities \( \rho \) of each aggregate and the volume \( V \) of them found in table (2). After these calculations, the necessary dosage of the concrete mixture for the six specimens is found, as shown in the table (3); in the same way, it should be considered that each quantity is doubled, because in the design the realization of two specimens was proposed for each strength.

\[
\rho = \frac{m}{V} \tag{3}
\]

Table 3. Concrete dosage for two specimens with dimensions 0,15 x 0,30 m

| Resistance (psi) | Cement (kg) | Sand (kg) | Gravel (kg) | Water (l) |
|-----------------|-------------|-----------|-------------|-----------|
| 3500            | 4,4532      | 10,656    | 10,301      | 2,3326    |
| 2500            | 3,1809      | 7,6341    | 14,759      | 1,8025    |
| 1500            | 2,2266      | 7,9522    | 15,374      | 1,6965    |

Once the quantity of material required is established, the mixture is developed for the three concrete strengths as explained below:

For the construction of concrete specimens, suitable molds must be used to shape and resist the cylinders; the molds used are made of solid iron, with dimensions of 15 cm in diameter and 30 cm in length, it should be noted that the height of the specimen must correspond twice the diameter. Before melting the concrete, it must be verified that the cylindrical specimens, are in good condition and properly covered, by a thin layer of mineral oil in its interior, this component prevents the concrete from sticking to the instrument.

The molds to be used must be covered in three layers in a progressive manner by the concrete mixture, in each phase, these layers must be applied proportionally to the size of the specimen, that is, occupying the same volume as shown in the figure (5). To perform this procedure, it is necessary to use a smooth rod 5/8 "in diameter, which will be embedded in each layer, emitting 25 strokes evenly; likewise, the use of a rubber hammer is required, to that in each of the layers of the procedure, between 10 and 15 additional hits are generated around the molds, in order to suitably compact the material.
Once the concrete specimens have been made, they must be unmolding over a period of 18 to 24 hours and transferred to a humid area, thus initiating the curing process, this is a process by which chemical hydration reactions occur of the cement components, mainly silicates and aluminates. Finally, in the final phase of the process; the specimens must be constantly hydrated with water for a period of 28 days, so that the concrete can reach the maximum strength with which it was designed. Figure (6) shows the specimens made.

Figure 6. Concrete specimen.

5. Measurement of the ultrasonic pulse velocity for each one the concrete specimens.
After 28 days of curing time of the concrete specimen, the ultrasonic pulse velocity is measured for each, so the experiment shown in figure (3) was performed, using the ultrasound equipment with reference to HUMBOLDT HC-6390, the generates an ultrasonic pulse signal as shown in figure (7), allowing to vary the maximum amplitudes of the signal, between 250[V], 500[V], 750[v] and 1000 V. In addition, 55 k[Hz] resonance frequency transducers were used. In this case the amplitude of the chosen ultrasonic pulse was 500[V], in turn, white vaseline was used acting as an acoustic coupling between the transducers and the surface of the concrete.

The respective test is performed for each specimen, and the signal generated by the receiving transducer is captured, Figure (8) shows a captured signal for a 3500psi specimen, in this one can observe the approximate flight time of the ultrasonic wave, taking into account that the equipment produces a small exciting on the receptor transducer that reference the initial time, in turn, it can be seen how some time later voltage variations begin to be noticed corresponding to the sound wave received by the transducer, thus the time between the reception of the signal and the initial time, corresponds to the flight time of the ultrasonic wave. For figure (8), the approximate flight time is 73μ[s].

Finally, the table (4) shows the corresponding measured flight time values, and the ultrasonic pulse velocity calculated for each of the concrete specimens.
Figure 7. Ultrasonic pulse signal generated by the HUMBOLDT HC-6390 with a maximum amplitude of 500 [V].

Figure 8. Signal obtained from the receiver transducer, where it is possible to observe the flight time of the ultrasonic wave, through one of the 3500psi specimens.

Table 4. Flight times measured and ultrasonic pulse velocity calculated for each of the specimens

| Concrete Specimen | Flight time [μs] | Ultrasonic pulse velocity [m/s] |
|-------------------|-----------------|---------------------------------|
| P1 3500psi        | 73,53           | 4080,0                           |
| P2 3500psi        | 72,76           | 423,11                           |
| P1 2500psi        | 81,30           | 3690,0                           |
| P2 2500psi        | 80,31           | 3735,                            |
| P1 1500psi        | 82,43           | 3639,5                           |
| P2 1500psi        | 82,72           | 3626,7                           |
6. Conclusion
Taking into account the results obtained from table (4), it can be seen that the measured ultrasonic pulse velocity is related to the compressive strength of concrete, because higher ultrasonic pulse velocity were obtained in the 3500psi specimens, lower in the 1500psi specimen, and intermediate in the 2500psi specimen, thus demonstrating that if the compressive strength of the concrete specimen increases, therefore the measured ultrasonic pulse velocity will also do this, this implies that the ultrasonic pulse velocity measurement technique implemented gives a notion about the quality of the concrete tested.

With the obtained results it is possible to classify the concrete specimen according to the ultrasonic pulse velocity, so based on [10] and [11], if a velocity greater than 4575[m/s] the concrete is considered excellent, if the velocity is between 3660 [m/s] and 4575 [m/s] the concrete is considered good, if it is between 3050 [m/s] and 3660[m/s] the concrete is considered to be questionable, if it is between 2125 [m/s] and 3050 [m/s] considered to be poor concrete, and if the velocity is less than 2125 [m/s] it is considered very poor quality concrete. Thus, according to the Classification mentioned Above, it is found that the specimen made of 3500 psi and 2500 psi respectively are in the quality range of good concrete, However, the Ultrasonic pulse velocity Measured on the 1500 psi specimen, suggests that their quality is questionable, which is reasonable due to their low compression strength.

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