CONCRETE AS A SOUND ABSORPTION MATERIAL

Theoretical models used as simple predictive tools for architects

Index

1. Concrete

The dome of the Pantheon is one of the most famous and ancient structures in concrete. Thanks to this it is easy to say that concrete is a material used since the time of the Ancient Romans, and probably even before. With the fall of the Roman Empire, the use of concrete became rarer, until the mid-eighteenth century when it was rediscovered. The concrete is a composite material, composed of aggregate, which can have different sizes from small stones of a few centimeters to the fine as sand, incorporated with the cement, also called binder, which fills the spaces between the particles of the aggregate fixing them together. The strength and versatility of this material allows experimentation with different shapes, surfaces and structural elements.

There are two types of concrete due to its manufacture: cast-in-place concrete and prefabricated concrete.

Cast-in-place concrete is a building material that uses a temporary form to shape liquid concrete until it hardens [1].

In 1905 John Alexander Brodie exhibited the first prefabricated concrete cottage at Cheap Cottage Exhibition in Letchworth. From this, was created the first block of prefabricated concrete panels, in Eldon Street in Liverpool, designed to as a solution to the housing shortage. Brodie was a pioneer in the use of concrete for the construction of prefabricated houses [2].

The idea of using concrete as a prefabricated was born because it is a very versatile material. In fact, it can be poured into molds where it hardens into rigid sections of almost any shape and size. Its advantage consists in, unlike for example of metal materials, it does not require heat and the mold does not have to be broken and reformed every time a section is created. Although it does not constitute an advantage in terms of weight and thermal conductivity, concrete is an economic material, available everywhere and highly resistant to the elements [3].

The precast concrete elements can be used for any part of the structure. Most often, these are structural elements, manufactured for economic reasons, to save time and money. One of the great advantages of precast concrete compared to cast in place concrete is its factory production, i.e. it takes place in a controlled environment without the weather variable. This allows to control quality such as density, color and finish. Instead, one of its biggest drawbacks is transportation; in fact, it is possible that the elements will be damaged during it [4].

1.1. Case study of the use of concrete

MAGMA ART AND CONGRES,
Santa Cruz de Tenerife, Tenerife, Spain, 2005
Architects: Fernando Menis, Felipe Artengo, José Mª Rodríguez-Pastrana
Acoustics: Pedro Cerda, Antonio Carrion

The building is located in a very dry environment but strongly marked by the presence of the sea and the profile of the volcanic mountains on the horizon. The project was born as the union of both landmarks, sea and mountains, combining large blocks of concrete, which incorporate lava stones, with a fluid cover that symbolically resembles the sea. The building thus creates a visual connection with the landscape through its shapes, textures and colors.

It consists of thirteen volumes that emerge from the ground, each containing different functions. The spaces between the concrete blocks allow natural light and ventilation to pass through them, the roofing, in contrast to the monolithic blocks, is like a dynamic fluid that welcomes all the different functions inside the building below [5].

The building is mainly made of concrete, and is designed to meet the most stringent requirements in terms of sound quality and versatility of use. The main hall can be used for a wide range of events. It is possible to change its configuration: it can act as an auditorium for three thousand spectators or, it can be transformed, through soundproof panels, into multiple rooms with a maximum of three hundred seats for each. Therefore, the main room has special acoustic requirements, which have been solved with an innovative technique. The finished rough walls were broken manually after the structure, with a pneumatic hammer, to produce irregular surfaces that made the concrete sound good. The acoustic system has been completed with hidden acoustic panels in order to fine-tune the sound effects. Even through the materials, we tried to integrate the building with the environment, to the cement was mixed the chasnera, volcanic stone extracted from the local quarries. For the roof, on the other hand, cement panels with vegetable fiber have been used, the shaded color of these panels recalls the color of the local natural stone [6].

IGLESIA DEL SANTISIMO REDENTOR,

San Cristobal de La Laguna, Tenerife, Spain, 2009

Architect: Fernando Menis

Acoustics: Audioscan

The building consists of a single piece of cement, broken into four volumes, separated from one another. Its architecture wants to imitate the irregularity of nature, recalling the action of time and natural elements. The building is located at a lower level than its surroundings. Access to the church is via a winding walkway with steps and zig-zag ramps. The building is on three levels: the ground floor, the loggia of worship, which extends from the presbytery up to the middle of the central nave, above the second half of the nave, there are two other floors with classrooms and offices. The cracks in the various volumes allow the light to enter to illuminate specific elements at different times of the day [7].

The entire building is in exposed concrete, never used in a homogeneous way, it creates a series of very natural shades different from the outside of the building. What looks like a rocky complex on the outside is, inside, like a cave with rough walls bush-hammered by lapilli [8].

Lapilli are a volcanic material widely used in the Canary Islands. The high porosity of the lapilli provides a significantly higher degree of sound absorption at medium and high frequencies, compared to traditional concretes. Thanks to this technique, it was possible to respect the materiality of the space, using it for its sound-absorbing characteristics in a highly reverberating space, thus avoiding the use of the usual porous materials that would have distorted the building's design. This type of concrete significantly improves speech intelligibility. The strong volumetric impact of the building and the use of essential materials, such as cement, the play of light and the possibility of a gradual construction of the four modules allow the church to optimize its economic resources. Create a timeless and exciting space [9].

CKK JORDANKI,
Torund, Poland, 2015
Architect: Fernando Menis
Acoustics: Pedro Cerda
The building is located within a green ring around the historic city center, overlooking the Vistula River. Particular attention has been given to the orientation and height of the volumes so, the new building establishes a harmonious relationship with the natural and built environment. The building occupies half of the area, the other half is dedicated to park and the height of the building is kept as low as possible, so as not to block the view over the river. The visual effect of a natural object, a rock, situated in a gently sloping meadow, has thus been reached [10].
The outer skin, in white cement, is a rigid casing that encloses the internal part that, like a fluid, brings together the different functions. Holes and cuts made in the rigid shell allow the red inner part, obtained with the Picado technique, to filter out. The red is given by the presence of crushed bricks mixed with cement, creating a contemporary reinterpretation of traditional brick, referring to the facades of this city, UNESCO heritage [11].
Picado, which is the Spanish word for chipped, consists of mixing the concrete with other materials and breaking after assembly, to obtain acoustic effects.
Through an interactive process, the spaces of the auditorium and its forms have been defined, always in relation with the acoustics, until reaching the final form. Thanks to the plastic properties of concrete, it is easy to use it in concert halls, as it is possible to check the geometry and adapt its shape to the formwork to control the first sound reflections received from the listener [12]. Surface treatment with crushed bricks mixed with concrete forms an irregular surface for high frequency diffusion (2000Hz). This material, unlike the flat surfaces which have an hard specular reflection, is able to smooth the sound of the first orchestral reflections. In this way, the same effect is obtained that the baroque architects obtained by adding decorations and ornaments. Brick surfaces minimize low frequency absorption to the minimum to provide fullness in the low end. In order to avoid acoustic glare, the MLS (Maximum Length Sequence) loudspeakers have been integrated into the mobile walls. The subterranean aspect of the room is reinforced by its asymmetry that contributes to a completely diffused reverberation field and a sense of winding making the audience feel surrounded by the sound. The surfaces have been carefully sized and oriented to improve the lateral reflections and provide a strong spatial feeling to the audience. The ceiling is composed of five mobile panels, with a surface ranging from 80 to 140 m^2 and weighing between 11 and 20 tons. The panels, which are also made of

concrete, have a steel skeleton and are covered in concrete to guarantee a sufficient density for the desired acoustic performances. Moving the panels, the volume of the space can be transformed from large, 8200 m^3 with a reverberation time of 1.85s (T30, 1.78s when occupied), reduced, 6800 m^3, bringing the ceiling to minimum height and breaking down the reverberation time at 1.35 s, inserting banners above and below the panels the reverberation time is further reduced to 1.2 seconds.
The room is able to cover the whole range of possible activities, 1.85s for symphonic music, 1.6s for the opera up to 1.2s for the theater [13].

1.2. References

[1] J. Ferrando, *Architectural material & detail structure : concrete*. London, 2016.

[2] “Liverpool Heroes 1: John Alexander Brodie, City Engineer | Historic Liverpool.” [Online]. Available: https://historic-liverpool.co.uk/liverpool-heroes-1-john-alexander-brodie-city-engineer/. [Accessed: 26-Oct-2018].

[3] A. Bruce, *A history of prefabrication*. Raritan, N.J., 1945.

[4] M. Peck, *Concrete : design construction examples*. .

[5] “Magma Arte & Congresos, Adeje, Tenerife (España Spain), 1998-2005,” *AV Monogr. = AV Monogr.*, vol. 181, pp. 34–43, 2016.

[6] “Fernando Menis: Magma Art and Congress Centre, Tenerife, Canary Islands, Spain.,” *GA Doc.*, vol. 107, pp. 80–97, 2009.

[7] “Holy Redeemer Church, Tenerife, Spain, 2007: Fernando Martin Menis,” *A + U Archit. Urban.*, vol. 1520, pp. 134–135, 2014.

[8] “Iglesia del Santísimo Redentor = Holy Redeemer Church, La Laguna, Tenerife (España / Spain), 2005-2008,” *AV Monogr. = AV Monogr.*, vol. 181, pp. 64–69, 2016.

[9] “Fernando Menis, Holy Redeemer Church.” [Online]. Available: https://divisare.com/projects/309579-fernando-menis-holy-redeemer-church. [Accessed: 07-Nov-2018].

[10] “Congress Centre Jordanki / Menis Arquitectos.” [Online]. Available: https://brickarchitecture.com/projects/congress-centre-jordanki-menis-arquitectos. [Accessed: 07-Nov-2018].

[11] “Centro cultural y de congresos Jordanki = Jordanki Cultural and Congress Center, Toruń, (Polonia Poland), 2008-2015,” *AV Monogr. = AV Monogr.*, vol. 181, pp. 80–91, 2016.

[12] “Fernando Menis: Culture and Congress Center Jordanki, CKK Jordanki, Torun, Poland, design 2009-11, construction 2013-15.,” *GA Doc.*, vol. 138, pp. 110–129, 2016.

[13] “AV Asia Pacific Magazine THE HALL THAT DOES IT ALL - AV Asia Pacific Magazine.” [Online]. Available: http://www.av.net.au/wp/index.php/the-hall-that-does-it-all/. [Accessed: 19-Nov-2018].

[14] J. Mairs, “Fernando Menis combines crushed brickwork and concrete for cavernous concert hall in Poland,” *Zeen*, 2016.

[15] “Polish concert hall is made with Picado concrete - MaterialDistrict.” [Online]. Available: https://materialdistrict.com/article/concert-hall-picado/. [Accessed: 07-Nov-2018].

2. Sound absorption

Sound absorption is the capacity of a material to absorb and eventually reflect the incident sound energy [1]. The materials and the absorbent elements are widely used in the acoustic treatment of the environments, to reduce the reverberated sound energy. Their use allows to control the reverberation time and the total sound pressure level present in the environment. The absorption of the emitted sound energy is one of the most effective noise reduction method when sound propagation occurs within closed spaces or when it is intended to isolate a source with respect to the surrounding environment. Absorbent materials are also applied to the acoustic barriers to reduce sound reflection from the surface [2].

The sound wave that strikes a surface can be partly reflected, partly absorbed and partly transmitted. Sound absorption can be described as the conversion of the acoustic energy into thermal energy by a surface [3].

The absorbing properties of the materials are quantified through the acoustic absorption coefficient, α, an adimensional coefficient defined as the ratio between the absorbed sound energy and the total incident energy on the material. Therefore, the numerical value of the absorption coefficient represents, the percentage of the acoustic energy that is absorbed by a material, and ranges between 0, in the case in which all the energy is reflected, and 1, in the case in which all the energy is absorbed.

The coefficient is dependent on frequency and angle of incidence of the acoustic wave [2]. Three different phenomena explain how sound absorption works: absorption by porosity, absorption by cavity resonance and absorption by membrane resonance.

In the porous absorbers, absorption is due to the phenomenon of viscosity: the dissipation of the sound wave occurs by transforming the sound into kinetic energy when the sound passes through the material. The sound-absorbing capacity is influenced by the density and thickness of the material. The absorption by porosity is generally high at the medium and medium-high frequencies and a high thickness of the material is required to obtain a significant damping of the low frequencies.

The most common cavity resonance absorbers are the Helmholtz resonators. They are constituted by a volume of air contained in a cavity with rigid walls, connected to the external environment through a relatively narrow opening, called the neck of the resonator. When an acoustic wave impinges on the neck of the resonator, the small mass of air contained inside the neck is put into vibration, and in turn, the air present inside the cavity undergoes compression and periodic rarefaction. The air inside the neck behaves like a vibrating mass while the air in the cavity behaves like an acoustic spring. This creates the classic mass-spring elastic system. The absorption of a resonator of this type is very selective around the resonance frequency, and therefore very effective in the case of pure tones of medium frequency, as for example, modes of vibration of environments, typically in the range between 200 Hz and 1000 Hz.

Membrane resonance absorbers work with a principle similar to that used for the Helmholtz resonator. In this case, the system consists of a panel positioned in front of a rigid surface, a few tens of centimeters. The panel behaves like a vibrating mass and the air contained in the cavity like an acoustic spring, thus creating a mass-air-mass system, which also comes into play to achieve sound insulation performances. The panel resonates at its coincidence frequency and the sound energy is damped by the air-cushion behind it. The maximum absorption frequency decreases as the specific mass and the depth of the air gap between the panel and the wall increases. As with Helmholtz resonators, the absorption of resonant panels is very selective around the resonance frequency [2].

2.1. Sound absorption in porous material

A porous absorbent material is generally a solid, which contains cavities, channels or interstices, with typical dimensions of less than 1mm. A material can have two different types of pores: closed pores and open pores. The closed pores, totally isolated from the others, influence the macroscopic properties of the material, but they are not effective in relation to the absorption of the acoustic energy. Open pores constitute a channel of communication with the outer surface of the material and have a decisive influence on the absorption of sound. The open pores may be blind, i.e. open at one end, or rings, open at both ends. By convention, there is a distinction between porosity and roughness, a rough surface is not porous, unless the depth of the irregularities exceeds its width.

Porous materials, acoustically absorbent, are generally divided into: porous cells, such as open cell polyurethane foams, fibrous, such as wood fibers, glass wool, mineral fibers, and granular, including asphalts, porous concrete, expanded clay, used for noise reduction in the external environment [2].

The propagation of sound into a porous material occurs in the pore network. During propagation, the acoustic energy is dissipated thanks to the thermal and viscous effects. In a small environment such as the pore of porous absorbers, the sound energy is lost through the effects of a viscous boundary layer, i.e. the sound energy is dissipated through friction with the pores walls. There is also a loss of momentum due to changes in the flow as the sound moves through the irregular pores. The boundary layer in the air at the audible frequencies is submillimetre in terms of size, and consequently viscous losses occur in a small layer of air adjacent to the walls of the pores. In addition to viscous effects, there will be losses due to thermal conduction from air to absorbent material, but this is more significant at low frequency. An open-pore and interconnected structure is necessary for the occurrence of the absorption phenomenon [4]. Porous absorbers are more efficient at high and medium frequencies [5].

Often, porous absorbers are combined to increase to achieve better sound absorption. Covering the interior of a Helmholtz resonator with a porous absorbent material, due to the dissipative effects created in the cavity, the value of the absorption coefficient at the resonance frequency decreases, but the frequency range at which absorption is effective increases. The resonator switches from a mass-spring system to a damped mass-spring system. Also in the case of resonant panels, it is possible to extend the frequency range by inserting porous material into the air cavity [2].

2.2. Measurement

In the laboratory, the coefficient of absorption at normal incidence is measured, with the method of standing waves in tube, on small samples, and the coefficient of absorption by random incidence, in reverberating chamber, on large samples. Since in real conditions the acoustic waves generally affect at different angles, the random incidence absorption coefficient is the one that best approximates the real conditions [2].

2.2.1. Reverberation room

Reverberation room is an acoustic experiment room uses to evaluate the sound absorption coefficient and the sound transmission loss of acoustic material [8]. The sound absorption coefficient obtained with the reverberation room considers random incident sound from whole directions. Unlike the measurements obtained in the tube, the chamber, by considering the random incidence, simulates a real situation. This method is considered as expressing the average sound absorbing performance of a material and is widely used in acoustic designing of concert halls and for evaluating the sound absorption performance of various materials, including automotive interior materials and building materials [9].

The reverberation chamber test requires large sample size and dedicated test room, which make it expensive to undertake. It also only gives absorption coefficients; the impedance cannot be measured. Furthermore, this method provides only absorption coefficients and not impedance. Consequently, developers of absorptive materials will often use the impedance tube to build up an understanding of the material properties on small samples, before undertaking reverberation tests [5]. The reverberation room has reflective walls, floor and ceiling to realize the conditions of the diffuse sound field approximately within limited space. In the reverberation room, the energy of the sound travels from various directions, the reverberation time is extremely long, and sound pressure level distribution is almost uniform [8].

The specimen must have an area between 10 m^2 and 12 m^2. In case the volume of the room is greater than 200 m^3, the specimen size limit increases by a factor of $(V/200\,m^2)^{2/3}$ where V is the volume of the room.

The area to be chosen depends on the volume of the room and the absorption capacity of the specimen. The larger the room, the greater the test area, but in the case of specimens with a low absorption coefficient, the upper limits can be chosen [10].

To obtain an average result to reduce the effect of non-diffuseness, multiple source and receiver positions are used. The source is normally placed in the corner of a room, pointing into the corner, because it maximally excites the modes of the room and reduces the amount of direct radiation from the loudspeaker to the test sample. Receivers should be at least one meter from the room boundaries, room diffusers and the sample, and should be chosen to obtain a diverse sampling of the room volume [5].

The sound absorption coefficient is obtained from the two measured reverberation times when a specimen is placed in a reverberation room, and when the room is empty. The reverberation time is calculated from the decay of the sound pressure level as a function of time at a certain point in the room [11].

How to perform measurements is explained in the UNI EN ISO 354:2003.

In this normative is explained how do measurement of sound absorption in a reverberation room. As already mentioned above, the average reverberation time in the chamber is measured with and without the specimen. With this reverberation time, the equivalent sound absorption area of the specimen is calculated using the Sabine equation. In the case in which the samples cover a surface uniformly, such as in plane absorber or in the case of specified array of the specimen, the absorption coefficient is obtained dividing the equivalent sound absorption area of the specimen by the area of treated surface area. On the other hand, when the specimen consists of several identical objects, the equivalent sound absorption area of a single object is obtained by dividing the equivalent sound absorption area of the specimen by the number of objects.

The standard describes two methods for measuring the decay curve: the interrupted sound method and the integrated impulse response method.

The interrupted sound method is the result of a static process, one microphone/loudspeaker position is necessary to obtain an adequate repeatability in the measurement of the average of different decay curves or reverberation times.

The integrated impulse response method is a deterministic function and not the prone to statistical deviations, so no averaging is necessary. However, it requires more sophisticated instruments and data processing of the previous method [10].

To overcome one of the major disadvantages of using the reverberation room, the large dimension of the specimens that make the measurements expensive, the reverberation room has been designed in scale. A small-sized reverberation room, however, maintains the widespread field conditions. The results obtained at medium-high frequencies are accurate and comparable with those obtained in a standard reverberation room [12].

2.2.2. Kundt's Tube

The Kundt tube has been applied to the measurement of the absorption coefficient of materials. It is a very useful device for determining coefficients quickly and accurately. This tool performs tests under well define and controlled conditions. Its advantage lies in its small size, which makes possible to carry out the measurements in a standard room and does not require special test room, a modest request for support equipment and a small sample to carry out the measurements. This tool is mainly used for porous absorbers because it is not suitable for those absorbers that depend on the area for their effect such as

vibrating panels and large slat absorbers. This makes it ideal for material developers [4].
The tube usually has a circular cross section with rigid walls. A loudspeaker, placed on the opposite side of the sample, generates a plane wave propagation in the tube and the plane wave propagates down the tube before being reflected from the sample. A standing wave is set up within the tube. The sample's impedance alters how sound is reflected and, by measuring the resulting standing wave. It is possible to calculate the normal incidence absorption coefficient and surface impedance of the sample [5].
How to perform measurements is explained in the UNI EN ISO 10534-1 and 10534-2.
In 10534-1 it is explained how to determine the acoustic absorption coefficient with the stationary wave method. The specimen is mounted on one end of the tube while on the other a loudspeaker is mounted which generates an incident plane sinusoidal sound wave. The overlap of the incident wave with the wave reflected from the specimen produces a stationary wave pattern in the tube. The evaluation proceeds from the quanty measured, in linear or logarithmic scale, of the amplitude of the sound pressure at a minimum and at the maximum pressure. To calculate the reflection factor and the impedance are also determined the distance of the first sound pressure minimum from the reference plane, the surface where the specimen is placed, and the sound wavelength [6].
In 10534-2 instead, is explained the transfer function method. In this case too, the specimen is mounted at one end while the sound source is mounted at the other end. The source generates a flat wave and the sound pressures is measured in two positions near the specimen. The complex acoustic transfer function of the signals of the two microphones is deduced and used to calculate the normal-incidence complex reflection factor, the normal-incidence absorption coefficient, and the impedance ratio of the test material. Quantity is determined as function of the frequency with the frequency resolution that is determined by the sampling frequency and the record length of the digital analysis system used for the measurements. The usable frequency range depends on the width of the tube and on the space between the microphone positions. You can perform these measurements using two different methods: two-microphone method and one-microphone method. The two-microphone method is recommended for general purpose testing. Requires a correction procedure with a pre-test or an in-test to minimize the amplitude and characteristic phase differences between the microphones. This method combines speed, high accuracy, and ease of implementation.
The one-microphone method is recommended for the assessment of tuned resonators and/or precision. It needs the generation of particular signals and processing and takes more time. Even if it eliminates the phase mismatch between the microphones and allows the selection of the optimal microphone position for each frequency [7].

2.3. Bibliography

[1] E. Cirillo and L. Legoprint, *Acustica applicata*. McGraw-Hill, 1997.

[2] R. Spagnolo, *Acustica : fondamenti e applicazioni*. UTET, 2015.

[3] A. C. Van Der Linden and A. Zeegers, "A c o u s t i c s," 2006.

[4] F. A. Everest and T. Legoprint, *Manuale di acustica : concetti fondamentali, acustica degli interni*. Hoepli, 1996.

[5] P. Cox, Trevor J.; D'Anton, *Acoustic Absorber and Diffusers*. 2009.

[6] "1053401_2001_EEN.pdf." .

[7] "1053402_2001_EEN.pdf." .

[8] "Reverberation Room | Nihon Onkyo Engineering Co., Ltd." [Online]. Available: https://www.noe.co.jp/en/product/pdt3/pd3_02.html. [Accessed: 19-Sep-2018].

[9] "Alphas-LAB sound absorption coefficient measurement system in the reverberation room - Nihon Onkyo Engineering Co., Ltd." [Online]. Available: https://www.noe.co.jp/en/product/pdt2/pd12/detail02.html. [Accessed: 19-Sep-2018].

[10] British Standards Institution, "BS EN 20354:1993 ISO 354:1985 Acoustics — Measurement of sound absorption in a reverberation room," vol. 3, pp. 1–8, 2003.

[11] "Measurement system of the sound absorption coefficient in a reverberation room | Nihon Onkyo Engineering Co., Ltd." [Online]. Available: https://www.noe.co.jp/en/product/pdt3/mat/mat02.html. [Accessed: 19-Sep-2018].

[12] R. Del Rey, J. Alba, L. Bertó, A. Gregori, and A. Gregori, "Small-sized reverberation chamber for the measurement of sound absorption," *Mater. Construcción*, vol. 67, no. 328, p. 139, Sep. 2017.

3. Concrete as a sound absorption material

3.1. Acoustic properties of concrete

Designers use the properties of different materials for insulation, reflection or absorption to control noise. Concrete has the ability to reduce the transmission of sound through it. Standard concrete surfaces are good reflective surfaces. Thanks to its structural characteristics (flat, less porosity and high density), it can reflect almost 99% of the sound energy. Concrete is a poor sound absorber which can lead to echoes within enclosed spaces [1]. Several researches have worked on improving the sound absorption capacity of concrete creating other types with increased porosity.

3.2. Type of acoustic concrete

3.2.1. Porous concrete

Porous concrete or pervious concrete is a special concrete with high porosity that are intentionally fabricated for acoustic absorption or permeation. The high porosity is obtained with an interconnected voids content. The sound energy that propagates in interconnected voids is converted into heat and dissipated thanks to refraction and interference occurring inside the voids texture [2]. It has been used since 1852 in residential walls. Pervious concrete can be used as a structural material. The main use of this concrete is for streets in residential areas, driveways, sidewalks, parking lots and, more recently, highways shoulders and high volume roadways. Thanks to its porosity, it is largely used for sound barriers and traffic noise reduction. To work efficiently it needs two important characteristics: high permeability and sufficient strength to withstand light traffic. These properties tend to increase as the amount of voids increases. Pervious concrete is composed by coarse aggregate, cementitious materials, water admixtures and, in some cases, fibers. Carefully controlled amounts of water and cementitious materials are used to create a paste that forms a thick coating around aggregate particles without flowing off during mixing and placing [3].

3.2.2. Cellular concrete

Cellular concrete or lightweight concrete is a low-density material that has a homogeneous cell structure obtained by adding mixture gas or foam to the fresh cementation. It presents macroscopic air cells uniformly distributed. There are two methods used to form air cells: through blending foam in the mix or with a chemical reaction generating gas in the slurry. Based on its density, cellular concrete can be non-structural or semi-structural. Non-structural cellular concrete has insulating properties and its applications regard thermal and sound insulation, roof decks, fillings for slab-on-grade subbases, firewalls and underground thermal conduit linings. Semi-structural cellular concrete is obtained by the mixture with sand or lightweight aggregates. Its application are thermal and sound insulation of floors and roofs for cellular concrete at low density and for cast-in-place walls, floors and roofs for high density concrete [4].

3.3. Design parameters that influence sound absorption in porous concrete

3.3.1. Porosity

Porosity is a percentage value that represents empty spaces in the material. The pores in porous concrete materials are formed by the spaces left between raw aggregates.

Number, size and type of pores are the important factors to consider studying sound absorption mechanism in porous material. Enough pores on surface of material will allow sound wave to penetrate the porous material for maximum energy dissipation by friction [5].

In porous materials sound propagates in a network of interconnected pores, and is dissipated due to the frictional on the pore walls [6].

Increasing porosities slightly increases the frequencies at maximum absorption. On the other hand, if the pore size increases, maximum peak decreases. In a large pore, the frictional losses are low and there is not enough friction to dissipate the sound energy. Porosity is influenced by the pore size, pore to aperture size ratio, and pore length, in addiction to aperture length, is the synergetic effect of all these factors that dictate the effect of porosity in acoustic absorption [7].

3.3.2. Aggregate

The shape of pores can be determined by the gradation and shape of aggregates and thickness of cement rims, which are related to the target void ratio. Different types of aggregate can increase or decrease the absorption coefficient. Adding a good absorber as aggregate to the cement paste, makes possible to obtain a concrete with a good absorption capability [1]. The gradation of aggregates mainly affects the maximum acoustic absorption coefficient, but does not substantially influence the peak frequency. As the gradation of the aggregate increases, the absorption coefficient decreases. Also, if large aggregates are blended with smaller ones, a decrease is noticed, i.e. a more compacted concrete has a lower absorption capability [2].

3.3.3. Density

Density of material is one of the most important factor that influence the sound absorption behavior of the material. Materials with hight density normally will absorbed more sound energy due to more surface frictional between the sound wave and the porous elements [5]. Less dense and more open structure absorbs sound of low frequencies (500Hz). Denser structure performs better for frequencies above than 2000 Hz [8]. Concrete sample with low density absorbs more and looses the ability of reflect sound [9].

3.3.4. Thickness

The thickness of the absorbent material is one of the main parameters that influence the absorption performance. The sound absorption in porous materials has a direct relationship with the thickness at low frequency. When the material becomes thicker, increase the sound absorption only at low frequencies. However, at higher frequencies, the thickness of the material has less effect on the acoustic absorption [8], [10]. Increasing the sample thickness reduces the frequencies to maximum absorption, as well as the spacing between the peaks [7]. The frequency at the maximum absorption coefficient could be thought as a function between the wave velocity in the medium and the thickness of the sample. Being the wave speed in air constant, changing the thickness of the sample shift the peaks. With a high thickness, a shift of the absorption coefficient spectra towards lower frequencies will be seen.

3.4. Case studies of the use of concrete in acoustics

In this paragraph are presented some case study of the possible application of concrete as a sound absorption material.

a. Noise Barriers

- **Arenas et al.** [10]

Tab. 3.4.1.

Aggregate	Bottom ash
Frequencies	250-4000 Hz
Peak of absorption	1600 Hz 4000 Hz

In this article is used the coal bottom ash-band sound absorbing concrete to make highway noise barriers. Using this kind of concrete the noise barrier was classified as A2 category, like traditional concrete used in road noise barriers is classified. There are five categories, from the A0 with DLα = not determined to A4 with DLα > 11. The DLα is the single-number rating of sound absorption performance expressed as a difference of A-weighted sound pressure levels, in decibels. The A2 category has DLα from 4 to 7 [11]. From the results obtained, bottom ash from the traditional pulverized coal combustion can be potentially recycled manufacturing a multilayer product that complies with the specifications required for road traffic noise reducing devices according to the European standards. Therefore, the bottom ash-based noise barrier can compete with the traditional concrete barriers usually applied to reduce road traffic noise, not only in terms of sound absorption but in production cost as well.

- **Asdrubali et al.** [12]

Tab. 3.4.2.

Aggregate	Rubber crumbs
Frequencies	500-2000 Hz

Tab.3.4.3.

ID code	Description	Thickness	Grain	α average
0		19 mm		0.517
PB1	Double-component polyurethane resin, 20-50% binder concentration	48 mm	medium	0.593
PB2		21 mm	Medium	0.413
PB3		21 mm	Small	0.479
PB4		49 mm	50% small + 50% medium	0.514
PB5		20 mm	Small	0.545
PB6		25 mm	Small	0.521
PB7		18 mm	Small	0.533
EB1	Double-component polyurethane resin, 10-15% binder concentration	18 mm	Small	0.477
EB2		20 mm	Medium	0.349
EB2		22 mm	Small	0.601
EB4		21 mm	Medium	0.388
EB5		38 mm	Small	0.676
EB6		28 mm	50% small + 50% medium	0.549
EM1	Simple component epoxy resin	33 mm	Small	0.578
EM2		48 mm	Small	0.674
EM3		45 mm	Small	0.692
EM4		60 mm	Small	0.698
EM5		62 mm	small	0.754

In this study the researchers do the sound absorption coefficient measurement of different concrete samples made of rubber crumbs. This measurement proves that this material can be used to develop noise barriers.

- **Carbajo et al.** [13]

Tab. 3.4.4.

Aggregate	Porosity	Thickness	Frequencies

Small grain arlite	0,39	51 mm	1000-1400
Large grain arlite	0,38	50.7 mm	
Small grain vermiculite type 2	0,39	50.6 mm	
Large grain vermiculite type 2	0,37	50.5 mm	
Large grain vermiculite type 3	0,4	50.9 mm	

This research investigate the acoustic properties of porous concrete made from arlite and vermiculite lightweight aggregates. This kind of material can be used for passive noise reduction in the building industry, in noise barriers and in ground surface. The results indicate that these consolidated materials yield a relatively high sound absorption and can thus become a sustainable alternative to other commonly used solutions in practical applications.

- **Gandoman et al.** [14]

Tab.3.4.5.

Sample	Description	Density	Aggregate	Frequencies	NCR (noise reduction coefficient)
CC	Conventional concrete	2.35 g/cm^3		125-4000 Hz	11.07
GC0	Sustainable waste rubber geopolymer concretes	2.06 g/cm^3	0% waste rubber		10.6
GC2		2.01 g/cm^3	2% waste rubber		11.35
GC6		1.98 g/cm^3	6% waste rubber		14.25
GC10		1.89 g/cm^3	10% waste rubber		17.6
GC14		1.81 g/cm^3	14% waste rubber		16.1

In this article are studied sound barrier properties of sustainable waste rubber geopolymer concretes. They conclude that waste rubber geopolymer concrete exhibits superior sound barrier properties than conventional concrete.

- Kim et al. [15]

Tab.3.4.6.

Specimen	Aggregate type	Aggregate size	Density	Frequencies
N1-80-0	Crashed gravel	8-13 mm	1611 kg/m³	250-1000 Hz
N1-80-0.1			1716 kg/m³	
N2-80-0		13-19 mm	1611 kg/m³	
N2-80-0.1			1780 kg/m³	
N1-110-0		8-13 mm	1736 kg/m³	
N1-110-0.1			1813 kg/m³	
N2-110-0		13-19 mm	1775 kg/m³	
N2-110-0.1			1829 kg/m³	
N1-140-0		8-13 mm	1802 kg/m³	
N1-140-0.1			1802 kg/m³	
N2-140-0		13-19 mm	1763 kg/m³	
N2-140-0.1			1721 kg/m³	
LW1-140-0	Expanded shale	4-8 mm	1254 kg/m³	
LW1-140-0.1			1254 kg/m³	
LW2-140-0		8-12 mm	1189 kg/m³	
LW2-140-0.1			1189 kg/m³	
LW3-140-0		12-19 mm	1225 kg/m³	
LW3-140-0.1			1225 kg/m³	

This study investigate the influence of cement flow and aggregate type on the mechanical and acoustic characteristics of porous concrete. This kind of concrete is generally applied for concrete pavement or sound barriers, reducing the impact of highway noise.

b. Concrete panels

- Holmes et al. [1]

Tab.3.4.7.

Mix ID	Aggregate	Aggregate size	Density	Frequencies
1A	Crumb rubber	Dust	2265 Kg/m³	125-4000 Hz
1B			2180 Kg/m³	
1C		1-3 mm	2310 Kg/m³	
1D			2240 Kg/m³	
1E		2-6 mm	2350 Kg/m³	
1F			2320 Kg/m³	
1G		10-19 mm	2360 Kg/m³	
1H			2325 Kg/m³	
2A		none	2440 Kg/m³	

The researchers study the acoustic properties of concrete panels used as an external cladding as a means to prevent the passage of sound transmission into the property.

c. Pavement systems

- Abd Halim et al. [16]

Tab. 3.4.8.

Sample	Description	Aggregate	Aggregate size	Highest sound absorption frequencies
Control	Porous concrete paving blocks	Crushed granite	5-10 mm	500-550 Hz
PCPB8-5			5-8 mm	550-600 Hz
PCPB10-8			8-10 mm	600-650 Hz

In this article are study sound absorption and morphology characteristic of porous concrete paving blocks at different size of coarse aggregate.

3.5. References

[1] N. Holmes, A. Browne, and C. Montague, "Acoustic properties of concrete panels with crumb rubber as a fine aggregate replacement," *Constr. Build. Mater.*, vol. 73, pp. 195–204, 2014.

[2] H. K. Kim and H. K. Lee, "Acoustic absorption modeling of porous concrete considering the gradation and shape of aggregates and void ratio," *J. Sound Vib.*, vol. 329, no. 7, pp. 866–879, 2010.

[3] *Selected Technical Papers STP1551 Pervious Concrete*. 2018.

[4] *Significance of Tests and Properties of Concrete & Concrete-Making Materials*. 2018.

[5] E. M. Samsudin, L. H. Ismail, and A. A. Kadir, "A review on Physical Factors Influencing Absorption Performance Offibrous Sound Absorption Material From Natural Fibers," *ARPN J. Eng. Appl. Sci.*, vol. 11, no. 6, pp. 3703–3711, 2016.

[6] P. Cox, Trevor J.; D'Anton, *Acoustic Absorber and Diffusers*. 2009.

[7] N. Neithalath, A. Marolf, J. Weiss, and J. Olek, "Modeling the Influence of Pore Structure on the Acoustic Absorption of Enhanced Porosity Concrete," *J. Adv. Concr. Technol.*, vol. 3, no. 1, pp. 29–40, 2005.

[8] H. S. Seddeq, "Factors Influencing Acoustic Performance of Sound Absorptive Materials," *Aust. J. Basic Appl. Sci.*, vol. 3, no. 4, pp. 4610–4617, 2009.

[9] U. Sandberg and J. A. J. Ejsmont, "ACOUSTICALLY EFFICIENT CONCRETES THROUGH ENGINEERED PORE STRUCTURE Narayanan Neithalath, Jason Weiss, and Jan Olek," *Cellulose*, p. 640, 2002.

[10] C. Arenas, C. Leiva, L. F. Vilches, H. Cifuentes, and M. Rodríguez-Galán, "Technical specifications for highway noise barriers made of coal bottom ash-based sound absorbing concrete," *Constr. Build. Mater.*, vol. 95, pp. 585–591, 2015.

[11] G. Parker, "Effective Noise Barrier Design and Specification Chair CEN TC226/WG6/TG1 for Road Traffic Noise reducing Devices," 2006.

[12] F. Asdrubali, F. D'Alessandro, and S. Schiavoni, "Sound absorbing properties of materials made of rubber crumbs," *J. Acoust. Soc. Am.*, vol. 123, no. 5, pp. 3037–3037, 2008.

[13] F. D. Carbajo, J., Esquerdo-Lloret, T.V., Ramis, J., Nadal-Gisbert, A.V., Denia, "Acoustic properties of porous concrete made from arlite and vermiculite lightweight aggregates," *Mater. Construcción*, vol. 65, no. 320, pp. 1–11, 2015.

[14] M. Gandoman and M. Kokabi, "Sound barrier properties of sustainable waste rubber/geopolymer concretes," *Iran. Polym. J. (English Ed.*, vol. 24, no. 2, pp. 105–112, 2015.

[15] H. K. Kim and H. K. Lee, "Influence of cement flow and aggregate type on the mechanical and acoustic characteristics of porous concrete," *Appl. Acoust.*, vol. 71, no. 7, pp. 607–615, 2010.

[16] N. H. Abd Halim *et al.*, "Sound absorption and morphology characteristic of porous concrete paving blocks," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 271, no. 1, 2017.

4. Theoretical models

4.1. Sound absorption theoretical models

It is possible as well as experimentally obtain the sound-absorbing properties of a material also through theoretical models.
With theoretical models can be obtained the acoustic absorption coefficient at normal incidence, for this reason the accuracy of the model is verified experimentally with the measurements in the Kunds tube.
The theoretical models are subdivided by three different approaches: empirical, phenomenological, microstructural. Empirical approach models are elaborated directly by the experimental results. Phenomenological approach models are based on the phenomenon of propagation within the pores. Microstructural approach models, on the other hand, apply a simplification of the internal structure of the porous material.
The data required by the different models are not always the same. There are models that use acoustic parameters, i.e. those parameters used to describe the properties of the porous material and how propagation occurs within the pores. Other models use non-acoustic parameters, which can be measured directly on the material. At last, some models use both types.
The data that most influences the absorbing properties of a material is the thickness, in fact this datum is fundamental for all theoretical models.
In addition to the thickness, all the models require the parameters that describe the environmental conditions in which the measures are carried out as: ρ_0 air density, c_0 speed of sound in air, P_0 ambient atmospheric pressure, γ specific heats ratio of air, η dynamic viscosity of air.
All the models obtain the sound absorption coefficient starting by the acoustic impedance. The acoustic impedance of an absorbing layer with a hard-back in case of normal incidence is calculated using the following expression: [1]

	$Z = Z_R + jZ_I$	(4.1.1.)

Z_R is the real part and Z_I is the imaginary part of acoustic impedance. Or: [2]

	$\mathrm{Z} = Z_s \, coth(-ik_s t)$	(4.1.2.)

Where Z_s is the complex characteristic acoustic impedance and k_s the complex wave number of the absorbing material and, t, is the thickness of the material. The sound absorption coefficient at normal incidence is then calculated as: [1]

	$\alpha_0 = \dfrac{4Z_R\rho_0c_0}{\lvert Z_I\rvert^2 + 2\rho_0c_0Z_R + (\rho_0c_0)^2}$	(4.1.3.)

Or using the normal incidence reflection R_e: [2]

	$R_e = \dfrac{Z_i - Z_0}{Z_i + Z_0}$	(4.1.4.)
	$\alpha_0 = 1 - \lvert R_e\rvert^2$	(4.1.5.)

Where Z_0 is the air characteristic impedance:

	$Z_0 = \rho_0 c_0$	(4.1.6.)

These equations are at the bases of the following approaches.

4.2. Approaches

4.2.1. Empirical

The empirical approach based models rely on experimental results. The leading model is presented by Delany-Bazley [3]. The success of this model is due to its simplicity; it needs only one parameter, the flow resistivity of the material, to calculate sound absorption. This model is based on many experimental measurements with the impedance tube, on fibrous material with high porosity, close to unity [1]. However, it is not very accurate especially at lower frequencies. Delany-Bazley equations have been further improved and adapt to different materials [1], [2], [4]–[8]. Another empirical approach is given by Voronina [9]–[12]. This approach is based on physical parameters, that is, porosity, tortuosity, airflow resistivity and diameters of the apertures.

4.2.2. Phenomenological

Phenomenological approach base models rely on the essential physics of acoustic propagation on a porous medium [13]. This approach calculates characteristic impedance and propagation wavenumber by the microscopic propagation through the pores [14]. The porous medium is considered as a compressible fluid where the dissipation of acoustic energy occurs [15]. For the continuum mechanics it is required that the wavelength of sound should be much larger than the size of the pore. In the porous material, acoustic waves propagate only in the fluid so, it can be seen as an equivalent fluid [16]. This approach studies the phenomenon of the viscous frictions on the pore walls [17], [18]. These models use only acoustical parameters. Most of the time however, some parameters are not possible to calculate inside the model, so it is necessary measure these parameters separately [19].

4.2.3. Microstructural

Microstructural approach based models rely on the simplification of the inner structure of the pores [2]. This approach derive the propagation of waves inside a single pore and then generalize the result for the whole material [1]. It starts by the simplification of the microscopic structure of the pore. The model developed by Zwikker and Kosten [20] simplify the pore structure as a regular stock of unconnected cylindrical parallel capillary tube. The solution has been written in terms of Bessel functions of complex arguments [20]. Also Biot [17], [18] based his model on the same simplification of the pore structure. Biot describes the wave propagation in a porous saturated material. This material is made by a solid matrix fully saturated with a fluid [21]. This theory defines the equations of the motion for the displacement and strain tensor of the air in the pores and the frame of the porous absorber [22]. These equations include coefficients to take into account physical properties such as bulk modulus of air in the pore and the elastic frame. Padè [23] approximation of the Biot's theory [23], was used for the acoustical properties of rigid-framed porous materials. It derives acoustical properties for media with size distribution of variously shaped pores.

4.3. Acoustical parameters

This kind of parameter can be used to describe the properties of porous materials and the propagation path through the pore. However, these parameters are rarely available, more awkward to measure, but are used in almost all the theoretical models [24].

4.3.1. Flow resistivity

The flow resistance is a physical quantity that characterizes the properties of open porosity materials respect to sound absorption and vibration dissipation properties. For a maximum absorption, the value of flow resistivity must be within certain limits: if it is too high, the acoustic waves do not penetrate into the material, on the other hand if it is too low, the waves do not meet a viscosity, a sufficient friction to dissipate energy.

The flow resistivity is define as:

$$\sigma = \frac{\Delta p}{q_v} \qquad (4.3.1.1.)$$

Where Δp is the difference in pressure applied to the two ends of the material to force a flow of air through it with volumetric velocity q_v. Tt is representative of the resistance opposed by the material to the flow of air. In homogeneous materials, the resistance is proportional to the thickness, t, and inversely proportional to the cross-sectional area, A, it is possible to define it as normal, σ_n, respect to the thickness and the surface of the test sample:

$$\sigma_n = \frac{\Delta p}{q_v} \frac{A}{d} \qquad (4.3.1.2.)$$

The relationship, which links the pressure difference to the volumetric speed, is only verified if the airflow is laminar and the volumetric velocity is sufficiently low. The flow resistivity depends on the materials' internal geometry, but also on the properties of the fluid that passes through it. It is related to the intrinsic permeability of Darcy, k_d, and to the dynamic viscosity of the air, η:

	$\sigma_n = \frac{\eta}{k_d}$	(4.3.1.3.)

The flow resistivity measurement consists in the generation of a flow of air through the sample and determination of the pressure drop at the two ends of the sample. The normative, ISO 9053, 1991 and UNI EN 29053, 1994, indicates two different measurement procedures, based respectively on the generation of a continuous or alternating airflow. The main problem is to determine very low pressure drops. It is often preferred to make the measurements in alternating flow regime, because in this way the pressure differences can be detected simply by means of microphone transducers [25]. It is possible to achieve the flow resistance experimentally with the following acoustic technique based on the measurement of the sinusoidal pressure component in a closed volume. In the closed volume, the air is subjected to a slow cycle of compression and rarefaction, using only a transducer, a low-frequency pressure field microphone, the intrinsic permeability of a porous medium is determined. The system generates an alternating air flow, from 0.1 Hz to 1 Hz, in a closed cavity, where the porous medium is placed on the walls of the cavity. The sinusoidal pressure is measured with a capacitive microphone placed in the closed cavity. The non-linear effects of the Ergun-Wu equation are excluded from the generated alternate flow rates that are sufficiently low. The permeability is determined based on the ratio between the volumetric air flow rate and the pressure in the closed cavity, according to Darcy's law.

	$k = \frac{q}{p}\frac{\mu t}{A_s}$	(4.3.1.4.)

The volumetric airflow depends on the geometric dimensions of the piston and the oscillation frequency

	$q = \frac{\pi}{\sqrt{2}} f h A_p$	(4.3.1.5.)
	$p = 1.4 \frac{P_0}{\sqrt{2}} \frac{V_{pk}}{V_c}$	(4.3.1.6.)

Where A_s is the effective surface area of the sample, f is the frequency oscillation of the piston, h is the stroke of the piston, A_p is the piston surface area, V_{pk} is the air volume moved by the piston, V_c is the volume of the cavity [26].

4.3.2. Porosity

Porosity is a percentage value that represents empty spaces in the material. The pores in the concrete are formed by the spaces left by the raw aggregates. There are two types of porosity: the effective porosity, that is the fraction of measurable voids migrated by fluids, and the total porosity, sum of the measurable voids between the aggregates and the air trapped in the cement paste.

The effective porosity can be measured experimentally measuring the volume of water displaced by the specimen. The specimen is oven dried at 110 °C and then immersed in water for at least 24 hours. The difference in the water level is then measured before and after the specimen is immersed.

$$\phi_e = \frac{V_b - V_d}{V_b} 100 \tag{4.3.2.1.}$$

Where V_b is the sample bulk volume, V_d is the volume of water repelled by the sample [27].

It is also possible obtain the effective porosity, knowing the flow resistivity, with the Ergun equations[28]. Darcy's law can determine the intrinsic permeability by measuring the volumetric flow rate and the pressure loss through a porous medium.

$$\frac{\Delta P}{t} = \frac{Q_v}{k}\frac{\mu}{A_s} = \frac{\mu}{k}U \tag{4.3.2.2.}$$

In 1952 Ergun found a more general equation.

$$\frac{\Delta P}{t} = 150\frac{(1-\phi)^2}{\phi^3}\frac{\mu U}{{D_p}^2} + 1.75\frac{\rho(1-\phi)}{\phi^3}\frac{U^2}{D_p} \tag{4.3.2.3.}$$

If the flow is kept laminar Darcy's law and Ergun's equation, subsequently modified by Wu, can be equal:

$$\frac{\phi^3}{\tau(1-\phi)^2} = 72\frac{k}{{D_p}^2} \tag{4.3.2.4.}$$

From the development of the Taylor series the equation can be written as a function of porosity.

$$\phi^4\left(\frac{5}{2}\phi + 2\right) = 72\frac{k}{{D_p}^2} \tag{4.3.2.5.}$$

This equation can be solved graphically by finding the zeros of the function [26].

It is hard to test accurately the total porosity of a concrete, this depends on its complex microstructure, the pores can be present from the nano-scale to the macro-scale [27]. The total porosity includes closed pores and open pores, which can be measured thanks to the Archimede's principle with the buoyancy floating apparatus. It is necessary to identify the total volume, V, dry mass, W_1, submerged mass, W_2, and water density, ρ_w [29]

$$\phi_t = \left[1 - \left(\frac{W_1 - W_2}{\rho_w V}\right)\right] * 100 \tag{4.3.2.6.}$$

Another way to determinate the total porosity is using the following equation:

$$\phi_t = \left(1 - \frac{\rho_m}{\rho_a}\right) \tag{4.3.2.7.}$$

Where ρ_m, is the bulk density of the material and ρ_a, is the apparent density, determined by measuring its dimensions and weight [30].

4.3.3. Tortuosity

Tortuosity is a parameter related to the characteristics of flow and transport in porous media. Tortuosity is the average ratio of the lengths of the distance that a fluid has to travel from a point to a final destination through the pore space of a porous medium with the length of the straight path between the starting point and the arrival point. In acoustics, tortuosity is a significant parameter that influences the propagation of sound and its velocity variations within the pore [31].
Starting from the Ergun equation it is possible to calculate the tortuosity depending on the porosity. Yu and Li propose the following simplification of the equation:

$$\tau = \frac{1}{2}\left[1 + \frac{1}{2} - \sqrt{1-\phi} + \sqrt{1-\phi}\,\frac{\sqrt{\left(\frac{1}{\sqrt{1-\phi}} - 1\right)^2 + \frac{1}{4}}}{1 - \sqrt{1-\phi}}\right] \quad (4.3.3.1.)$$

4.3.4. Thermal characteristic length

The thermal characteristic length is the size of the region with the largest surface area between the pore networks where the heat dissipation of sound energy is highly in favor. It controls the thermal effects at medium and high acoustic frequencies. The thermal characteristic length can be estimated with measurements in the standing wave tube or with ultrasound techniques [30].

4.3.5. Viscous characteristic length

The viscous characteristic length is a parameter used to describe the viscous effects at medium and high frequencies. It is the dimension of the constriction section in the pore network where the viscous dissipation of the sound energy is dominant. In a porous material composed of pores and inter-connections, viscous effects mainly occur in inter-connections. It is possible to estimate the viscous characteristic length with the same techniques used for the thermal characteristic length [30].

4.4. Non-acoustical parameters

The non-acoustical parameters are all input data easy to calculate. They are all the parameter that describe the sample, like shape or dimensions of the aggregate.

4.4.1. Geometric model of porosity

The geometric model of the porosity consists of a series of alternating cylinders of different diameters, each unit of the pore network is formed by pores and apertures. The pore-apertures unit is the basic cell of the model. The porosity of the material is defined by the diameter and length of pores and apertures.

$$\phi = \frac{\left({D_a}^2 L_a + {D_p}^2 L_p\right)}{\left(L_a + L_p\right)\left(D_p + t\right)^2} \qquad (4.4.1.1.)$$

To obtain an acoustic absorption spectrum, the geometry of the pores is modeled using an electro-acoustic analogy, formed by a series of resistors and inductors in parallel.

4.4.2. Gradation of the aggregate

The gradation of the aggregate is its dimension. It is possible to find as a radius of the aggregate, average of the distribution of the aggregate radius, or as the diameter of the aggregate, average of the distribution of the aggregate diameters [32].

4.4.3. Pore shape factor ratio

the pore shape factor ratio describe the difference of acoustical behaviors between fibrous and granular materials, his range from 0,6 to 1 [5].
It is determined by the geometry of the pore, considering cylindrical pores the pore shape factor ratio is 1 [33].

4.4.4. Shape of the aggregate

Porous concrete can be considered as an ordered assembly of spherical aggregates. This simplification forms a uniform lattice. The uniform lattice can be considered as a perforated panel, formed by the layer of aggregates, with air gap between the panels. The shape of the aggregates influences the thickness of the air gap. The aggregate shape factor can have a value of 1 in the case of a packed lattice, and a value of 2 in the case of a rhombic lattice. Considering an ellipsoid aggregate, it will have a value of 1,1 because it has a less compact reticule compared to a lattice formed with a spherical aggregate, which has 1 as a shape factor [32].

4.4.5. Standard deviation of the pore size

The standard deviation of the pore size is a measure that quantifies the pore size dispersion. It is obtained from a curve representing the pore size value with a log-normal distribution. The pore size can be obtained with the water suction method. With this method is also possible to obtain the average pore size and the inner pore area for consolidate and non-consolidated porous samples [20].

4.4.6. Target void ratio

The target void ratio is the volume of voids, in percentage, in the porous materials. It is possible to calculate the void ratio with the following equation:

$$TVR = \left[1 - \frac{(W_1 - W_2)}{V}\right] * 100 \qquad (4.4.6.1.)$$

Where W_2 is the weight of the specimen under water, W_1 is the weight of the specimen following 24 h exposure to the air, V is the volume of the specimen [34].

4.4.7. Thermal pore shape factor

Thermal pore shape factor treat the effect of pore shape factor on the thermal function. It is possible to obtain with the following equation:

$$S_k = \frac{8K'_0}{\phi \Lambda'^2} \qquad (4.4.7.1.)$$

Where K_0' is the static thermal permeability, ($K_0' = 1/\Gamma$), Γ is the tapping constant, ϕ is the porosity, Λ' is the thermal characteristic dimension [35].

4.4.8. Viscous pore shape factor

Viscous pore shape factor treat the effect of pore shape factor on the viscous function. It is possible to obtain with the following equation:

$$S_p = \frac{8\tau K_0}{\phi \Lambda^2} \qquad (4.4.8.1.)$$

Where K_0 is the static viscous permeability, ($K_0 = \eta/\sigma$), η is the air viscosity, σ is the flow resistivity, ϕ is the porosity, Λ is the viscous characteristic dimension [35].

4.5. Concrete's theoretical models

The following theoretical models were selected after a review of the different articles about theoretical models for sound absorption. The review started with two different keywords: "acoustical absorption model for porous material" and "acoustical absorption model for porous material". The research was conducted with the PICO database resource of the Politecnico di Torino. In this research, only the articles were selected. The selection process was divided into three rounds Fig.4.5.1.

The first round was based on the title, all the articles whose titles were not related to the topic were excluded. The second round was based on the content of the abstracts, all the articles that did not concern porous or granular materials and all those that did not specify a sound absorption model were excluded. The third round was based on a quick reading of the entire article, excluding items that did not deal with a concrete-like material and all those where the implementation of a theoretical model was not specified. All these searching process is described in detail in Fig.4.5.2. At the end of the research process, only thirteen articles were able to suit all the rounds criteria. The articles have been organized in the Tab.4.5.1. In this table are described for each article the material used in the study, the theoretical model, the approach used in the model, the data required by each model, and the results obtained in the articles by comparing the data of the models with those measured.

Tab. 4.5.1.

Summary of the papers Included after the third review round

MATERIAL	APPROACH	MODEL	PARAMETERS	INPUT DATA (definition is given in APPENDIX A)	RESULTS	REF.
Porous Concrete	microstructural	Electro-Acoustic analogy	Non Acoustic	Target void ratio	Good agreement between calculated and measured maximum absorption coefficient peak and the corresponding peak frequencies of all the specimens. **Fig.3.(a)**	[32]
				Gradation of the aggregates		
				Shape of aggregate		
Porous Road Pavement	phenomenological	Hamet-Berengier	Acoustic	Porosity	There is a close agreement between the two models and with the measured data. **Fig.3.(b)**	[14]
				Tortuosity		
				Flow resistivity		
	microstructural	Champoux-Stinson	Acoustic	Porosity		
				Tortuosity		
				Flow resistivity		
			Non acoustic	Viscous pore shape factor		
				Thermal pore shape factor		
Perforate Concrete	microstructural	Horoshenkov-Swift	Acoustic	Porosity	The predicted curves show less sound absorption than measured **Fig.3.(c)**	[28]
				Tortuosity		
				Flow resistivity		
				Standard deviation of the pore size		
Porous zeolite with macropores (Porous ceramic material)	empirical	Delany-Bazley	Acoustic	Flow resistivity	JA model conforms to experimental results better than DB model does. **Fig.3.(d)**	[30]
	phenomenological	Johnson-Allard	Acoustic	Porosity		
				Tortuosity		
				Flow resistivity		
				Viscous characteristic length		
				Thermal characteristic length		

<table>
<tr><th>MATERIAL</th><th>APPROACH</th><th>MODEL</th><th>PARAMETERS</th><th colspan="2">INPUT DATA</th><th>RESULTS</th><th>REF.</th></tr>
<tr><td rowspan="4">Enhanced porosity concrete</td><td rowspan="4">microstructural</td><td rowspan="4">Electro-Acoustic analogy</td><td rowspan="4">Non Acoustic</td><td colspan="2">Diameter of the pores</td><td rowspan="4">Good correlation between measured and predicted values, and the first absorption peak match well. Fig.3.(e)</td><td rowspan="4">[15]</td></tr>
<tr><td colspan="2">Length of the pore</td></tr>
<tr><td colspan="2">Diameter of the apertures</td></tr>
<tr><td colspan="2">Length of the apertures</td></tr>
<tr><td rowspan="4">Consolidate expanded clay granulates</td><td rowspan="4">microstructural</td><td rowspan="4">Horoshenkov-Swift</td><td rowspan="4">Acoustic</td><td colspan="2">Porosity</td><td rowspan="4">No comparison between theoretical and experimental data</td><td rowspan="4">[36]</td></tr>
<tr><td colspan="2">Tortuosity</td></tr>
<tr><td colspan="2">Flow resistivity</td></tr>
<tr><td colspan="2">Standard deviation of the pore size</td></tr>
<tr><td rowspan="3">Rigid frame porous material with high porosity</td><td rowspan="3">empirical</td><td rowspan="3">Voronina</td><td rowspan="2">Acoustic</td><td rowspan="2">Porosity</td><td>Measured bulk density of the porous material</td><td rowspan="3">No comparison between theoretical and experimental data</td><td rowspan="3">[9]</td></tr>
<tr><td>Density of the rigid frame</td></tr>
<tr><td>Non acoustic</td><td colspan="2">Pore diameter</td></tr>
<tr><td rowspan="4">Granular materials</td><td rowspan="4">microstructural</td><td rowspan="4">Horoshenkov-Swift</td><td rowspan="4">Acoustic</td><td colspan="2">Porosity</td><td rowspan="4">Good agreement is reported as a result of a close match between the measured and predicted surface impedance. Fig.3.(f)</td><td rowspan="4">[20]</td></tr>
<tr><td colspan="2">Tortuosity</td></tr>
<tr><td colspan="2">Flow resistivity</td></tr>
<tr><td colspan="2">Standard deviation of the pore size</td></tr>
<tr><td rowspan="4">Porous asphalt concrete</td><td rowspan="4">microstructural</td><td rowspan="4">Electro-Acoustic analogy</td><td rowspan="4">Non acoustic</td><td colspan="2">Diameter of the pores</td><td rowspan="4">The difference in percentage between estimate and measured absorption peak is lower than 2% for frequency and absorption coefficient. Fig.3.(g)</td><td rowspan="4">[37]</td></tr>
<tr><td colspan="2">Length of the pore</td></tr>
<tr><td colspan="2">Diameter of the apertures</td></tr>
<tr><td colspan="2">Length of the apertures</td></tr>
</table>

MATERIAL	APPROACH	MODEL	PARAMETERS	INPUT DATA	RESULTS	REF.
Porous materials	empirical	Delany-Bazley-Miki	Acoustic	Flow resistivity	Has not been verified that the model provides a good prediction in the frequency range from 400 to 2000 Hz but it can be said that the model is well behaved in that range.	[6]
Porous materials	empirical	Delany-Bazley-Miki	Non acoustic	Pore shape factor	No comparisons between theoretical and experimental data	[5]
			Acoustic	Porosity		
				Tortuosity		
				Flow resistivity		
Porous materials	microstructural	Champoux-Stinson	Acoustical	Porosity	No comparisons between theoretical and experimental data	[35]
				Tortuosity		
				Flow resistivity		
			Non acoustical	Viscous pore shape factor		
				Thermal pore shape factor		
Porous concrete	microstructural	Horoshenkov-Swift	Acoustic	Porosity	Good agreement between the predictions and the experimental data, it is verify in the range 500 - 1800 Hz some discrepancies over 1800 Hz and low frequency range occur. **Fig.3.(h)**	[38]
				Tortuosity		
				Flow resistivity		
				Standard deviation		

4.5.1. Delany-Bazley-Miki

Tab.4.5.1.1.

MODEL	APPROACH	PARAMETARS	INPUT DATA
Delany-Bazley	empirical	acoustical	flow resistivity
		non-acoustical	thickness
Delany-Bazley-Miki	empirical	acoustical	flow resistivity
		non-acoustical	thickness

In 1990 Miki[5], [6], implemented a model based on Delany-Bazley's theory [3]. Using the experimental data from Delany-Bazley, Miki proposed new constants for the normalized impedance. This model uses an empirical approach. It is useful for the prediction of acoustical behavior of porous materials, especially in the double-layer case, even outside the frequency range of validity of the original models. In the case of multiple layer, in Delany Bazley model the real part of the surface impedance sometimes becomes negative at low frequency range. This phenomenon is due to the fact that existing impedance must be a positive-real function whereas that of their models cannot satisfy this property. To satisfy this property Miki propose new constants for the normalized impedance [6].
The empirical equations for the modification of Delany Bazley by Miki are: [1]

$$\alpha = \left(\frac{2\pi f}{c_0}\right)\left(C_5\left(\frac{\rho_0 f}{\sigma}\right)^{-C_6}\right) \tag{4.5.1.1.}$$

$$\beta = \left(\frac{2\pi f}{c_0}\right)\left(1 + C_7\left(\frac{\rho_0 f}{\sigma}\right)^{-C_8}\right) \tag{4.5.1.2.}$$

$$Z_r = \rho_0 c_0\left(1 + C_1\left(\frac{\rho_0 f}{\sigma}\right)^{-C_2}\right) \tag{4.5.1.3.}$$

$$Z_i = -\rho_0 c_0\left(C_3\left(\frac{\rho_0 f}{\sigma}\right)^{-C_4}\right) \tag{4.5.1.4.}$$

Where α and β are the real and imaginary parts of the characteristic propagation constant, Z_r and Z_i are the real and imaginary parts of the characteristic acoustic impedance.

Tab.4.5.1.2.
Values of the eight coefficients in Eqs. (4.5.1.1.)–(4.5.1.4.) from the Delany-Bazley-Miki value compared with the values found by Delany–Bazley.

Model	**C_1**	**C_2**	**C_3**	**C_4**	**C_5**	**C_6**	**C_7**	**C_8**
Delany Bazley	0.057	0.754	0.087	0.732	0.189	0.595	0.098	0.700

Miki	0.070	0.632	0.107	0.632	0.160	0.618	0.109	0.618

In this case the needs only one acoustical parameter, that is the flow resistivity.
The characteristic impedance is obtain as:

$$Z_s = Z_r + jZ_i \tag{4.5.1.5.}$$

The propagation constant is:

$$k_s = \alpha + j\beta \tag{4.5.1.6.}$$

So it is possible to calculate the absorption coefficient using the normal reflection.

$$Z = Z_s \cot(-jk_s t) \tag{4.5.1.7.}$$

$$R = \frac{Z - Z_0}{Z + Z_0} \tag{4.5.1.8.}$$

$$\alpha_0 = 1 - |R|^2 \tag{4.5.1.9.}$$

Where Z_0 is the air characteristic impedance:

$$Z_0 = \rho_0 c_0 \tag{4.5.1.10.}$$

4.5.2. Miki generalization model

Tab.4.5.2.1.

MODEL	APPROACH	PARAMETARS	INPUT DATA
Miki generalization model	empirical	acoustical	flow resistivity
			porosity
			tortuosity
		non-acoustical	thickness

In 1990 Miki [5], [6], also developed a general model for porous material because sometimes the real part of the surface impedance gives a non-physical parameter at low frequencies.
Delany Bazley model is generalized respect to porosity, tortuosity and pore shape factor ratio. The new models have these three parameters besides the flow resistivity. For a practical use, the impedance model can be described with two parameters. The effective flow resistivity and the ratio of tortuosity to porosity. Compared with the original Delany Bazley model, the generalization have a greater applicability to various kinds of porous materials [5]. It is also possible to use it for a wide variety of ground surfaces thanks to the good agreement with the model by Attenborough [33].

$$Z_s = \frac{\tau}{\phi}\left(1 + 0.07\left(\frac{f}{\sigma_e}\right)^{-0.632} + 0.107i\left(\frac{f}{\sigma_e}\right)^{-0.632}\right) \tag{4.5.2.1.}$$

	$$k_s = \frac{\omega\tau}{c_0}\left(1 + 0.109\left(\frac{f}{\sigma_e}\right)^{-0.618} + 0.160i\left(\frac{f}{\sigma_e}\right)^{-0.618}\right)$$	(4.5.2.2.)

Where

	$$\sigma_e = \frac{\phi}{\tau^2}$$	(4.5.2.3.)
	$$Z_0 = \rho_0 c_0$$	(4.5.2.4.)
	$$R = \frac{\mathrm{Z} - Z_0}{\mathrm{Z} + Z_0}$$	(4.5.2.5.)
	$$\alpha_0 = 1 - \|R\|^2$$	(4.5.2.5.)

The second Miki develop model needs more input data but it is more accurate than the first.

4.5.3. Voronina

Tab.4.5.3.1.

MODEL	APPROACH	PARAMETARS	INPUT DATA	
Voronina	empirical	acoustical	porosity	bulk density of the material
				apparent density of the material
		non-acoustical	thickness	
			pore diameter	

In 1997 Voronina [9] proposed an empirical model for rigid framed porous material with high porosity (foam-gypsum, foam-slag concrete, foam-ceramic). In Rayleigh's theory for a capillary tube model of a porous medium the fractional losses have been described by two relations. The first of them is a relation between the pore diameter, D, and the viscous boundary layer thickness, the second relation is again between the pore diameter and the sound wave length. This introduce two dimensionless physical parameters z and y, for a quantitative estimation of energy losses in one of the channels. They have been defined as:

	$$z = \sqrt{\frac{D\rho_0 c_0}{\eta}}$$	(4.5.3.1.)
	$$y = \sqrt{kD}$$	(4.5.3.2.)

Where $k = \omega/c_0$, is wave number, D corresponds to the maximum of the pore diameter distribution obtained experimentally by a standard method. The summary effect depends on pore volume per unit material volume or porosity. To simplify the model the value Q has been introduced as an acoustic parameter and called structural characteristic.

$$Q = \frac{14.1(1-H)}{Hzy} = \frac{1-H}{HD}\sqrt{\frac{200\mu}{k\rho_0 c_0}} \quad (4.5.3.3.)$$

The real part of the characteristic impedance is:

$$Z_r = 1 + Q \quad (4.5.3.4.)$$

In case of Q < 1

$$Z_i = \frac{Q}{2} \quad (4.5.3.5.)$$

$$\alpha = kQ \quad (4.5.3.6.)$$

In case Q >1 these parameters can presented as:

$$Z_i = \frac{Q}{2+a} \quad (4.5.3.7.)$$

$$\alpha = \frac{kQ}{2+a} \quad (4.5.3.8.)$$

The value a, is a factor that tends to zero at low frequencies and it can be found as follow:

$$a = \frac{Q}{\left(1+\sqrt{Q}\right)^2} \quad (4.5.3.9.)$$

In case of phase constant the imaginary part of the characteristic propagation constant is:

$$\beta = k\big(1 + Q(1+B)\big) \quad (4.5.3.10.)$$

Where B, is a coefficient that depends on the structural characteristic.

$$B = (60x^2 - 120x + 61{,}5)^{-1} \quad (4.5.3.11.)$$

$$x = \frac{120m}{z(1+Q)} \quad (4.5.3.12.)$$

Where x is a variable by means of which all curves B(f) can be combined into one curve B(x), and $m = 10^3\,\rho_o/\rho_a$.

In case of the value of x is included between 0,5 and 1,5 the imaginary part of the characteristic propagation constant is:

$$\beta = k(1 + Q) \quad (4.5.3.13.)$$

The characteristic impedance and propagation constant function are:

$$Z_s = Z_r + jZ_i \quad (4.5.3.14.)$$

$$k_s = \alpha + j\beta \quad (4.5.3.15.)$$

The sound absorption coefficient is:

	$$Z = Z_s \cot(-jk_s t)$$	(4.5.3.16.)
	$$Z_0 = \rho_0 c_0$$	(4.5.3.17.)
	$$R = \frac{Z - Z_0}{Z + Z_0}$$	(4.5.3.18.)
	$$\alpha_0 = 1 - \lvert R \rvert^2$$	(4.5.3.19.)

This model needs only two input parameter: the maximum of the pore diameters distribution and porosity [9].

4.5.4. Hamet-Berengier

Tab.4.5.4.1.

MODEL	**APPROACH**	**PARAMETARS**	**INPUT DATA**
Hamet-Berengier	phenomenological	acoustical	flow resistivity
			porosity
			tortuosity
		non-acoustical	thickness

Hamet-Berengier is phenomenological model used in Berengier et al. [14] study. This approach introduces viscous dissipation and thermal dissipation, i.e. velocity gradient within the porous medium and the thermal gradients within the same medium, respectively. The thermal dissipation is important when airflow resistance is small and the material presents a highly porous structure [14]. The model requires only three parameters, porosity, tortuosity and flow resistivity. It is well-suited for material that have moderate porosity [1].

The dynamic density and bulk modulus functions are given by:

	$$\rho_g(\omega) = \rho_0 \tau \left(1 + j\frac{f_\mu}{f}\right)$$	(4.5.4.1.)
	$$K_g(\omega) = \gamma P_0 \left[\frac{1 + (\gamma - 1)}{\left(1 - j\frac{f}{f_\theta}\right)}\right]^{-1}$$	(4.5.4.2.)

Where f_μ describe the viscous dependencies and f_θ describe the thermal dependencies.

	$$f_\mu = \frac{\phi\sigma}{(2\pi\rho_0\tau)}$$	(4.5.4.3.)
	$$f_\theta = \frac{\sigma}{(2\pi\rho_0 N_{pr})}$$	(4.5.4.4.)

The complex wave number and the characteristic impedance may be written as:

	$$k_s = \omega \sqrt{\frac{\rho_g(\omega)}{K_g(\omega)}}$$	(4.5.4.5.)
	$$Z_s = \frac{1}{\phi} \sqrt{\rho_g(\omega) K_g(\omega)}$$	(4.5.4.6.)

The sound absorption coefficient is:

	$$Z = Z_s \cot(-jk_s t)$$	(4.5.4.7.)
	$$Z_0 = \rho_0 c_0$$	(4.5.4.8.)
	$$R = \frac{Z - Z_0}{Z + Z_0}$$	(4.5.4.9.)
	$$\alpha_0 = 1 - \lvert R \rvert^2$$	(4.5.4.10.)

4.5.5. Johnson-Allard-Champoux

Tab.4.5.5.1.

MODEL	APPROACH	PARAMETARS	INPUT DATA
Johnson-Allard-Champoux	phenomenological	acoustical	flow resistivity
			porosity
			tortuosity
			thermal characteristic length
			viscous characteristic length
		non-acoustical	thickness

Cuiyun et al. [30] use Delany Bazley [3] model and Johnson Allard model [39] (named Johnson-Allard-Champoux in other articles [2], [40]–[42]) for the acoustical analysis of porous zeolite. Johnson-Allard used a phenomenological approach to solve acoustic absorption for rigid framed porous material with acoustical parameters as input data. It is a five parameters model that considers porosity, tortuosity, flow resistivity and two characteristic lengths. Viscous characteristic length and thermal characteristic length describe the viscosity and thermal conductivity through the fluid and the frame. Thanks to these two parameters, it is possible to find the relationship between the micro-structure and the sound absorption properties of the material. This model proposed a solution for viscous diffusion at low and high frequencies [13]. In the research of Cuiyun et al. [30] has established that Johnson-Allard model fits the experimental result better than Delany-Bazley model.

The dynamic density and bulk modulus functions are given by:

	$$\rho_g(\omega) = \frac{\rho_0\tau}{\phi}\left(1 + j\frac{\sigma\phi}{\tau\rho_0\omega}\sqrt{1 + j\frac{4\tau^2\eta\rho_0\omega}{\sigma^2\Lambda^2\phi^2}}\right)$$	(4.5.5.1.)
	$$K_g(\omega) = \frac{\frac{\gamma P_0}{\phi}}{\gamma - (\gamma - 1)\left[1 - j\frac{8\eta}{\Lambda'^2 N_{pr}\rho_0\omega}\sqrt{1 + j\frac{\Lambda'^2 N_{pr}\rho_0\omega}{16\eta}}\right]^{-1}}$$	(4.5.5.2.)

The complex wave number and the characteristic impedance may be written as:

	$$k_s = \omega\sqrt{\frac{\rho_g(\omega)}{K_g(\omega)}}$$	(4.5.5.3.)
	$$Z_s = \frac{1}{\phi}\sqrt{\rho_g(\omega)K_g(\omega)}$$	(4.5.5.4.)

The sound absorption coefficient is:

	$$Z = Z_s\cot(-jk_s t)$$	(4.5.5.5.)
	$$Z_0 = \rho_0 c_0$$	(4.5.5.6.)
	$$R = \frac{Z - Z_0}{Z + Z_0}$$	(4.5.5.7.)
	$$\alpha_0 = 1 - \lvert R\rvert^2$$	(4.5.5.8.)

4.5.6. Champoux-Stinson

Tab.4.5.6.1.

MODEL	**APPROACH**	**PARAMETARS**	**INPUT DATA**
Champoux-Stinson	microstructural	acoustical	flow resistivity
			porosity
			tortuosity
		non-acoustical	thickness
			thermal pore shape factor
			viscous pore shape factor

Berengier et al. [14] says that Champoux-Stinson [35] is the model that best fits the acoustical properties for porous road surface. This is because this model uses two kinds of pore shape factor and treats separately viscous and thermal functions. It uses a microstructural approach based on Bessel functions. It needs five acoustical input data, such as: porosity, tortuosity, flow resistivity and two shape factors (thermal and viscous shape factors), one related to the thermal microstructure and the other with the viscous microstructure. Berengier et al. [14] compared Champoux-Stinson model with a phenomenological model (Hamet-Berengier) and with experimental results. They conclude that both the theoretical models fit well to the experimental data.

The thermal dependence is accounted for by the bulk modulus. This model uses the expression given by Zwikker and Kosten for the fluid bulk modulus [43]:

	$K_g(\omega) = \dfrac{\gamma P_0}{1 + \dfrac{2(\gamma - 1)T(\Lambda_k)}{\Lambda_k}}$	(4.5.6.1.)
	$\Lambda_k = \lambda_k \sqrt{-iN_{pr}}$	(4.5.6.2.)
	$\lambda_k = S_k \left[\dfrac{8\tau\rho_0\omega}{\sigma\phi}\right]^{\frac{1}{2}}$	(4.5.6.3.)

The viscous dependence is accounted for by the dynamic density. The dynamic density equation is written according the Biot Theory [43].

	$\rho_g(\omega) = \rho_0\tau - j\dfrac{\sigma\phi F(\lambda_p)}{\omega}$	(4.5.6.4.)
	$F(\lambda_p) = -\dfrac{1}{4}\dfrac{\lambda_p\sqrt{-i}T\left(\lambda_p\sqrt{-i}\right)}{1 - 2\dfrac{T\left(\lambda_p\sqrt{-i}\right)}{\lambda_p\sqrt{-i}}}$	(4.5.6.5.)
	$\lambda_p = S_p \left[\dfrac{8\tau\rho_0\omega}{\sigma\phi}\right]^{\frac{1}{2}}$	(4.5.6.6.)
	$T(\xi) = \dfrac{J_1(\xi)}{J_0(\xi)}$	(4.5.6.7.)

J_0 and J_1 are being the zero and first Bessel functions, S_k and S_p are thermal and viscous shape factors respectively.

The complex wave number and the characteristic impedance may be written as:

	$k_s = -\omega\sqrt{\dfrac{\rho_g(\omega)}{K_g(\omega)}}$	(4.5.6.8.)
	$Z_s = \dfrac{1}{\phi}\sqrt{\rho_g(\omega)K_g(\omega)}$	(4.5.6.9.)

The sound absorption coefficient is:

	$Z = Z_s \cot(-jk_s t)$	(4.5.6.10.)

	$$\alpha_0 = 1 - \left|\frac{Z - \rho_0 c_0}{Z + \rho_0 c_0}\right|^2$$	(4.5.6.11.)

4.5.7. Horoshenkov-Swift

Tab.4.5.7.1.

MODEL	APPROACH	PARAMETARS	INPUT DATA
Horoshenkov-Swift	microstructural	acoustical	flow resistivity
			porosity
			tortuosity
		non-acoustical	thickness
			standard deviation of the pore size

This model was used in Carbajo et al.[38] research to predict acoustic properties of porous concrete made by arlite and vermiculite lightweight aggregates, and in Vasina et al. [36] study, for consolidated expanded clay granulates. This model has a microstructural approach starting by Padè approximation. This approximation proposes a simple method for the prediction of the acoustic properties of rigid framed porous media with log normal distribution pore size [23]. It uses four acoustical parameters, such as: tortuosity, porosity, flow resistivity and standard deviation of the pore size. These input data was determined with an experimental setup [20]. There is a good agreement between the predicting and experimental results especially in the frequency range from 500 to 1800 Hz.

The rigid frame porous media is modelled as a stack of parallel capillary tubes. In this model thermal and viscous effect in tortuous pores are treated separately. The thermal effects are expressed by the complex expression for the compressibility of the fluid:

	$$C_b = \frac{\phi}{\gamma P_0}\left[\gamma - \frac{\rho_0 \tau(\gamma - 1)}{\phi\rho\left(N_{pr}\omega\right)}\right]$$	(4.5.7.1.)

The viscous effects are expressed by the complex expression for the dynamic density:

	$$\rho_g = \frac{\tau}{\phi}\left(\rho_0 - \frac{\phi\sigma}{j\omega\tau}F(\omega)\right)$$	(4.5.7.2.)

F(ω) is the viscosity correction function, this function is presented in the form of a Padé approximation as:

$$F(\omega) = \frac{1 + a_1\varepsilon + a_2\varepsilon^2}{1 + b_1\varepsilon} \quad (4.5.7.3.)$$

With:

$$a_1 = \frac{\theta_1}{\theta_2} \quad (4.5.7.4.)$$

$$a_2 = \theta_1 \quad (4.5.7.5.)$$

$$b_1 = a_1 \quad (4.5.7.6.)$$

Being $\theta_1 = \frac{4e^{4\xi}}{3-1}$ and $\theta_2 = \frac{e^{\frac{3\xi}{2}}}{\sqrt{2}}$ for the circular pore geometry assumption, where $\xi = (\sigma_p \ln 2)^2$ and σ_p is the standard deviation in the log-normally distributed pore size, and $\varepsilon = \sqrt{\frac{-j\omega\rho_0\tau}{\sigma\phi}}$

The complex wave number and the characteristic impedance may be written as:

$$k_s = \omega\sqrt{\rho_g C_b} \quad (4.5.7.7.)$$

$$Z_s = \sqrt{\frac{\rho_g}{C_b}} \quad (4.5.7.8.)$$

The sound absorption coefficient is:

$$Z = Z_s \cot(-jk_s t) \quad (4.5.7.9.)$$

$$\alpha_0 = 1 - \left|\frac{Z - \rho_0 c_0}{Z + \rho_0 c_0}\right|^2 \quad (4.5.7.10.)$$

4.5.8. Electro-Acoustic Analogy

Tab.4.5.8.1.

<table>
<tr><th colspan="2">MODEL</th><th>APPROACH</th><th>PARAMETARS</th><th>INPUT DATA</th></tr>
<tr><td rowspan="7">Electro-Acoustic analogy</td><td rowspan="3">Kim et al.</td><td rowspan="7">microstructural</td><td rowspan="3">non-acoustical</td><td>target void ratio</td></tr>
<tr><td>gradation of the aggregate</td></tr>
<tr><td>shape of the aggregate</td></tr>
<tr><td rowspan="4">Neithalath et al.</td><td rowspan="4">non-acoustical</td><td>diameter of the pores</td></tr>
<tr><td>length of the pores</td></tr>
<tr><td>diameters of the apertures</td></tr>
<tr><td>length of the apertures</td></tr>
</table>

This model was used several times to calculate acoustical properties of concrete. Kim et al. [32] and Neithalath et al. [15] used it for porous concrete, and Losa et al. [37] for porous asphalt concrete. In the Kim et al. [32] research, this model was used because it does not consider acoustical parameters. This model has a microstructural approach and the porous scheme are simplified with Zwikker Kosten theory like numerous cylindrical apertures. This model is called electro-acoustical analogy since it considers the real component of the impedance of the apertures as resistors and the imaginary component as inductors. Also the impedance of the air inside the pore is modeled as a resistor, since the internal resistance of air in the pore is the product of the density of air and the speed of sound in air. It does not consider the thermal effects.

This model has two develop, the first develop is the one described by Kim et al. [32], the second develop is the one described by Neithalath et al. [15].

4.5.8.1. Kim et al. develop

This model is based on a microstructural approach. Porous concrete is considered as a uniform lattice composed by perforated panels made of aggregate layers and air gaps between the layers. The gradation and shape of the aggregates effects the thickness of air gaps. The method used to simplify the porous concrete structure is the “multy-layered perforated panel model” proposed by Kang et al. [44]. it is usually used for regular shaped perforated material, but Wang et al. [7] demonstrated that it is possible to use it for acoustic absorption modeling of materials with irregular shaped pores.

The aggregate assembly is simplified using the average gradation of aggregates as radius of aggregates, r, and the aggregate is assembled with surrounding six aggregates forming a hexagonal arrangement. Thanks to this simplification is possible to obtain the original perforate ratio as:

$$P_{origin} = \frac{\text{(area of a triangle)} - \text{(area of three hatched sectors)}}{\text{(area of a triangle)}} = \frac{\sqrt{3}r^2 - \frac{\pi}{2}r^2}{\sqrt{3}r^2} \cong 9.31\ percent \qquad (4.5.8.1.1.)$$

The P_{origin} not consider the shape of the apertures and the thickness of the cement rims, so it is introduced an effective perforated ratio:

$$P_{eff} = mP_{orogin} \qquad (4.5.8.1.2.)$$

m is a factor determinate through a fitting process in according with the peak frequency.

$$m = 1.106e^{8.4248(TVR)} \pm 0.121 \qquad (4.5.8.1.3.)$$

The diameter of the apertures is a function of the average gradation of aggregate:

$$d = 0.07r + 0.643 \qquad (4.5.8.1.4.)$$

The thickness of the panel, which composes the lattice, is:

$$t_{panel} = 2\left(\frac{2\sqrt{6}}{3} - 1\right) r \cong 1.266r \quad (4.5.8.1.5.)$$

The thickness of the air gap between the panels is:

$$t_{air} = \kappa\left(r - \frac{t}{2}\right) \cong 0.367\kappa r \quad (4.5.8.1.6.)$$

Where κ is the shape of aggregate.

The impedance of the apertures is define as:

$$Z_a = j\omega\rho_0 t_{panel}\left[1 - \frac{2}{\sqrt{-j}\beta'}\frac{J_1\sqrt{-j}\beta'}{J_0\sqrt{-j}\beta'}\right]^{-1} \quad (4.5.8.1.7.)$$

Where $\beta' = \frac{d}{2}\sqrt{\frac{\omega\rho_0}{\eta}}$

In case of large diameter apertures or high-frequency (β>10) the impedance of the apertures can be simplified as:

$$Z_a = \frac{8\eta t_{panel}\beta'}{\sqrt{2}d^2} + j\left(\omega\rho_0 t_{panel}\frac{8\eta t_{panel}\beta'}{\sqrt{2}d^2}\right) \quad (4.5.8.1.8.)$$

In case β′ has an intermediate value (1 < β′ < 10) can be simplified as:

$$Z_a = \frac{32\eta t_{panel}}{d^2}\sqrt{1 + \frac{\beta'^2}{32}} + j\omega\rho_0 t_{panel}\left(1 + \frac{1}{\sqrt{9 + \frac{\beta'^2}{2}}}\right) \quad (4.5.8.1.9.)$$

The acoustic impedance of the aperture considering the end effect is:

$$Z_a = R_a + jM_a \quad (4.5.8.1.10.)$$

$$R_a = \frac{32\eta t_{panel}}{d^2}\left(\sqrt{1 + \frac{\beta'^2}{32}} + \sqrt{\frac{\beta' d}{4t_{panel}}}\right) \quad (4.5.8.1.11.)$$

$$M_a = \omega\rho_0 t_{panel}(1 + \frac{1}{\sqrt{9 + \frac{\beta'^2}{2}}} + 0.85\frac{d}{t_{panel}} \quad (4.5.8.1.12.)$$

The impedance of the perforated panel is:

$$z_a = \frac{Z_a}{P_{eff}} \quad (4.5.8.1.13.)$$

The impedance of an air gap between two panels in case of $\frac{\omega t_{air}}{c_0} \ll 1$ is define as:

$$Z(t_{air}) = -j\rho_0 c_0 \cot\left(\frac{\omega t_{air}}{c_0}\right) \cong -j\frac{\rho_0 {c_0}^2}{\omega t_{air}} \quad (4.5.8.1.14.)$$

The impedance of a unit layer consisting of a panel and air gap is:

$$Z_1 = z_a + Z(t_{air}) \quad (4.5.8.1.15.)$$

In case of a series of n stacked layers, the impedance of the system can be:

$$Z_n = z_a + \frac{Z_{n-1}Z(t_{air})}{Z_{n-1} + Z(t_{air})} \quad (4.5.8.1.16.)$$

The acoustic absorption coefficient of a multi-layered panel system can be expressed as:

$$\alpha_0 = \frac{\frac{4R}{\rho_0 c_0}}{\left(1+\frac{R}{\rho_0 c_0}\right)^2 + \left(\frac{M}{\rho_0 c_0}\right)^2} \quad (4.5.8.1.17.)$$

Where R and M are the real and imaginary parts of the impedance of the multi-layer panel system [32].

4.5.8.2. Neithalath et al. develop

The electro-acoustic model represent the pores system as a series of resistors and inductors, the resistors represent the real component of the impedance of the apertures, and the inductors represent the imaginary component. The impedance of the air inside the pores is modeled as a resistors, since the internal resistance of air in the pore is the product of the density of air and the speed of sound in air [15]. The impedance of the air inside the pore is:

$$Z_P = -j\rho_0 c_0 \cot\left(\frac{\omega D_P}{c_0}\right) \quad (4.5.8.2.1.)$$

If $\left(\frac{\omega D_P}{c_0}\right) \ll 1$it is possible to simplify as:

$$Z_P = -j\frac{\rho_0 {c_0}^2}{\omega {D_P}^2} \quad (4.5.8.2.2.)$$

The acoustic impedance of the apertures is:

$$Z_a = R_a + jM_a \quad (4.5.8.2.2.)$$

$$R_a = \frac{32\eta L_A}{{D_A}^2}\left(\sqrt{1+\frac{\beta'^2}{32}} + \sqrt{\frac{\beta' D_A}{4L_A}}\right) \quad (4.5.8.2.3.)$$

$$M_a = \omega\rho_0 L_A(1 + \frac{1}{\sqrt{9+\frac{\beta'^2}{2}}} + \frac{8D_A}{3\pi L_A} \quad (4.5.8.2.4.)$$

Where $\beta' = \frac{D_A}{2}\sqrt{\frac{\omega\rho_0}{\eta}}$

The impedance of a unit layer consisting of a panel and air gap is:

$$Z_1 = z_A + Z_P = R + jM \quad (4.5.8.2.5.)$$

The specific acoustic impedance of apertures is:

$$z_A = Z_a\frac{{D_P}^2}{{D_A}^2} \quad (4.5.8.2.6.)$$

In case of a material sample with a certain thickness, composed by a series of n cells along the length of the sample, the acoustic impedance of the system is:

$$Z_n = z_A + \frac{1}{\frac{1}{Z_P} + \frac{1}{Z_{n-1}}} \quad (4.5.8.2.7.)$$

The acoustic absorption coefficient can be expressed as :

$$\alpha_0 = \frac{\frac{4R}{\rho_0 c_0}}{\left(1 + \frac{R}{\rho_0 c_0}\right)^2 + \left(\frac{M}{\rho_0 c_0}\right)^2} \quad (4.5.8.2.8.)$$

4.6. References

[1] M. Garai and F. Pompoli, "A simple empirical model of polyester fibre materials for acoustical applications," *Appl. Acoust.*, vol. 66, no. 12, pp. 1383–1398, 2005.

[2] P. Cobo and F. Simón, "A comparison of impedance models for the inverse estimation of the non-acoustical parameters of granular absorbers," *Appl. Acoust.*, vol. 104, pp. 119–126, 2016.

[3] M. E. Delany and E. N. Bazley, "Acoustical properties of fibrous absorbent materials," *Appl. Acoust.*, vol. 3, no. 2, pp. 105–116, 1970.

[4] R. Del Rey, J. Alba, J. P. Arenas, and V. J. Sanchis, "An empirical modelling of porous sound absorbing materials made of recycled foam," *Appl. Acoust.*, vol. 73, no. 6–7, pp. 604–609, 2012.

[5] Y. Miki, "Acoustical properties of porous materials - Generalizations of empirical models," *Jounral Acoust. Soc. Japan*, vol. 11, no. 1, pp. 25–28, 1990.

[6] Y. Miki, "Acoustical properties of porous materials-Modifications of Delany-Bazley models," *J. Acoust. Soc. Jpn.(E)*, vol. 11, no. 1, pp. 19–24, 1990.

[7] X. Wang and T. J. Lu, "Optimized acoustic properties of cellular solids," *J. Acoust. Soc. Am.*, vol. 106, no. 2, pp. 756–765, 1999.

[8] I. P. Dunn and W. A. Davern, "Calculation of acoustic impedance of multi-layer absorbers," *Appl. Acoust.*, vol. 19, no. 5, pp. 321–334, 1986.

[9] N. Voronina, "An empirical model for rigid frame porous materials with high porosity," *Appl. Acoust.*, vol. 51, no. 2, pp. 181–198, 1997.

[10] N. Voronina, "An Empirical Model for Elastic Porous Materials," *Appl. Acoust.*, vol. 55, no. 1, pp. 67–83, 1998.

[11] N. Voronina, "Improved empirical model of sound propagation through a fibrous material," *Appl. Acoust.*, vol. 48, no. 2, pp. 121–132, 1996.

[12] N. N. Voronina and K. V. Horoshenkov, "A new empirical model for the acoustic properties of loose granular media," *Appl. Acoust.*, vol. 64, no. 4, pp. 415–432, 2003.

[13] D. K. Wilson, "Simple, relaxational models for the acoustical properties of porous media," *Appl. Acoust.*, vol. 50, no. 3, pp. 171–188, 1997.

[14] M. C. Bérengier, M. R. Stinson, G. A. Daigle, and J. F. Hamet, "Porous road pavements: Acoustical characterization and propagation effects," *J. Acoust. Soc. Am.*, vol. 101, no. 1, pp. 155–162, 1997.

[15] N. Neithalath, A. Marolf, J. Weiss, and J. Olek, "Modeling the Influence of Pore Structure on the Acoustic Absorption of Enhanced Porosity Concrete," *J. Adv. Concr. Technol.*, vol. 3, no. 1, pp. 29–40, 2005.

[16] N. Sebaa, Z. E. A. Fellah, M. Fellah, W. Lauriks, and C. Depollier, "Measuring flow resistivity of porous

material via acoustic reflected waves," *J. Appl. Phys.*, vol. 98, no. 8, 2005.

[17] M. A. Biot, "Theory of Propagation of Elastic Waves in a Fluid-Saturated Porous Solid. I. Low-Frequency Range," *J. Acoust. Soc. Am.*, vol. 28, no. 2, pp. 168–178, 1956.

[18] M. A. Biot, "Theory of Propagation of Elastic Waves in a Fluid-Saturated Porous Solid. II. Higher Frequency Range," *J. Acoust. Soc. Am.*, vol. 28, no. 2, pp. 179–191, 1956.

[19] Z. Bo and C. Tianning, "Calculation of sound absorption characteristics of porous sintered fiber metal," *Appl. Acoust.*, vol. 70, no. 2, pp. 337–346, 2009.

[20] K. V. Horoshenkov and M. J. Swift, "The acoustic properties of granular materials with pore size distribution close to log-normal," *J. Acoust. Soc. Am.*, vol. 110, no. 5, pp. 2371–2378, 2001.

[21] I. Acoustics, "Chapter 7 Biot ' s theory for porous media," vol. 6, no. 1986, 2001.

[22] P. Cox, Trevor J.; D'Anton, *Acoustic Absorber and Diffusers*. 2009.

[23] K. V. Horoshenkov, K. Attenborough, and S. N. Chandler-Wilde, "Padé approximants for the acoustical properties of rigid frame porous media with pore size distributions," *J. Acoust. Soc. Am.*, vol. 104, no. 3, pp. 1198–1209, 1998.

[24] C. Hopkins, *Sound insulation*. Elsevier / Butterworth-Heinemann, 2007.

[25] R. Spagnolo, *Acustica : fondamenti e applicazioni*. UTET, 2015.

[26] A. Schiavi, C. Guglielmone, F. Pennella, and U. Morbiducci, "Acoustic method for permeability measurement of tissue-engineering scaffold," *Meas. Sci. Technol.*, vol. 23, no. 10, 2012.

[27] C. Lian, Y. Zhuge, and S. Beecham, "The relationship between porosity and strength for porous concrete," *Constr. Build. Mater.*, vol. 25, no. 11, pp. 4294–4298, 2011.

[28] A. Schiavi and L. Shtrepi, "Ergun-Wu Equation : A Novel Approach for the Determination of Physical Parameters in Low / Medium Porosity Materials," no. January, 2013.

[29] S. Lakusic, "Analiza svojstava procjednog betona," *J. Croat. Assoc. Civ. Eng.*, vol. 68, no. 06, pp. 493–501, 2016.

[30] D. Cuiyun, C. Guang, X. Xinbang, and L. Peisheng, "Sound absorption characteristics of a high-temperature sintering porous ceramic material," *Appl. Acoust.*, vol. 73, no. 9, pp. 865–871, 2012.

[31] R. I. Al-Raoush and I. T. Madhoun, "TORT3D: A MATLAB code to compute geometric tortuosity from 3D images of unconsolidated porous media," *Powder Technol.*, vol. 320, pp. 99–107, 2017.

[32] H. K. Kim and H. K. Lee, "Acoustic absorption modeling of porous concrete considering the gradation and shape of aggregates and void ratio," *J. Sound Vib.*, vol. 329, no. 7, pp. 866–879, 2010.

[33] K. Attenborough, "On the acoustic slow wave in air-filled granular media," *J. Acoust. Soc. Am.*, vol. 81, no. 1, pp. 93–102, 1987.

[34] S. B. Park, D. S. Seo, and J. Lee, "Studies on the sound absorption characteristics of porous concrete based on the content of recycled aggregate and target void ratio," *Cem. Concr. Res.*, vol. 35, no. 9, pp. 1846–1854, 2005.

[35] M. R. Stinson and Y. Champoux, "Propagation of sound and the assignment of shape factors in model porous materials having simple pore geometries," *J. Acoust. Soc. Am.*, vol. 91, no. 2, pp. 685–695, 1992.

[36] M. Vašina, D. C. Hughes, K. V. Horoshenkov, and L. Lapčík, "The acoustical properties of consolidated expanded clay granulates," *Appl. Acoust.*, vol. 67, no. 8, pp. 787–796, 2006.

[37] M. Losa and P. Leandri, "A comprehensive model to predict acoustic absorption factor of porous

mixes," *Mater. Struct. Constr.*, vol. 45, no. 6, pp. 923–940, 2012.

[38] F. D. Carbajo, J., Esquerdo-Lloret, T.V., Ramis, J., Nadal-Gisbert, A.V., Denia, "Acoustic properties of porous concrete made from arlite and vermiculite lightweight aggregates," *Mater. Construcción*, vol. 65, no. 320, pp. 1–11, 2015.

[39] J. Allard and Y. Champoux, "New empirical equations for sound propagation in rigid frame fibrous materials," *J. Acoust. Soc. Am.*, vol. 91, no. 6, pp. 3346–3353, 1992.

[40] N. Kino, "Further investigations of empirical improvements to the Johnson-Champoux-Allard model," *Appl. Acoust.*, vol. 96, pp. 153–170, 2015.

[41] N. Kino and T. Ueno, "Improvements to the Johnson-Allard model for rigid-framed fibrous materials," *Appl. Acoust.*, vol. 68, no. 11–12, pp. 1468–1484, 2007.

[42] S. Liu, W. Chen, and Y. Zhang, "Design optimization of porous fibrous material for maximizing absorption of sounds under set frequency bands," *Appl. Acoust.*, vol. 76, pp. 319–328, 2014.

[43] Y. Champoux and M. R. Stinson, "On acoustical models for sound propagation in rigid frame porous materials and the influence of shape factors," *J. Acoust. Soc. Am.*, vol. 92, no. 2, pp. 1120–1131, 1992.

[44] Y. J. Kang and J. S. Bolton, "Finite element modeling of isotropic elastic porous materials coupled with acoustical finite elements," *J. Acoust. Soc. Am.*, vol. 98, no. 1, pp. 635–643, 1995.

5. Experimental measurements

5.1. Samples description

The aggregate used are glass-ceramic spheres of 2-4 mm diameter. A cement paste, 218 Kg/m^3 dense, holds the aggregate together. The concrete obtained presents 25% of air voids and a total density of 514 Kg/m^3. With this mix, 18 panels measuring 54x54 cm with three different thicknesses were formed; three panels have a thickness of 20 mm, three are 40 mm thick and the last three are 60 mm thick. In addition to the panels, cylindrical specimens with a diameter of 50 mm have also been created for the three different thicknesses. The panels were used for reverberation room measurements, while the cylindrical specimens were used for measurements with the Kundt tube and for permeability and flow resistivity.

5.2. Theoretical models

Once the models suitable for measuring the cementitious materials have been selected, the models have been implemented on MATLAB and validated according to the data of the reference articles.

5.2.1. Parameters measurements

Tab.5.2.1.1.
Particle size distribution

sieve	Passing [%]
1.80 mm	8.40 %
2.00 mm	33.3 %
2.50 mm	55.4 %
2.80 mm	76.2 %
3.15 mm	91.2 %
3.55 mm	99.5 %
4.00 mm	99.7 %

Tab. 5.2.1.2.
Description of the panel through the known parameters

Aggregate	round glass-ceramic aggregate of 2-4 mm
Panel dimension	54x54 cm
Average aggregate diameter	3.2 mm
Air voids	25 %
Concrete density	218 Kg/m^3
Bulk density	190±20 Kg/m^3
Particle density	320±40 Kg/m^3
Density	514 Kg/m^3

Crushing resistance	1.4 N/mm^2		
Cylindrical specimens diameter	50 mm		
Pore diameter	1.4 mm		
Thickness	20 mm	40 mm	60 mm
Surface	0.29 m^2	0.38 m^2	0.42 m^2

Comparing the table 5.2.1.1. with the tables in chapter 4, that collect all the parameters necessary for each theoretical model, it is easy to understand that it is not possible to use any of the models with the available data. Therefore, further measures were necessary. One of the data that most appears in the models is the resistivity to the flow. The flow resistivity was measured experimentally using the method explained in section 4.3.1., the acoustic technique on the measurements of the sinusoidal pressure component in a closed volume. Thanks to this technique, it is possible to obtain not only the flow resistivity but also the permeability. Once the flow resistivity has been obtained, porosity and tortuosity can also be calculated, starting from the Ergun equation, as explained in paragraphs 4.3.2. and 4.3.3. The flow resistivity measurements were made only for the 20 mm thick sample.

Tab. 5.2.1.3.

Aggregate	Round glass-ceramic aggregate of 2-4 mm		
Panel dimension	54x54 cm		
Average aggregate diameter	3.2 mm		
Air voids	25 %		
Concrete density	218 kg/m^3		
Bulk density	190±20 Kg/m^3		
Particle density	320±40 Kg/m^3		
Density	514 kg/m^3		
Crushing resistance	1.4 N/mm^2		
Cylindrical specimens diameter	50 mm		
Pore diameter	1.4 mm		
Thickness	20 mm	40 mm	60 mm
Surface	0.29 m^2	0.38 m^2	0.42 m^2
Flow resistivity	8320 Ns/m^4		
Effective porosity	0.27658 %		
Tortuosity	2.2206 %		
Permeability	2.24E-09 m^{-2}		

With the data obtained, the models can be applied. Flow resistivity is the only parameter needed for Delany-Bazley-Miki. By calculating the porosity, it is also possible to use the Voronina, which requires only porosity and pore diameter. Also obtaining the tortuosity it is possible to apply models like Miki generalization model and Hamet-Berengier. Thanks to these few parameters, it is possible to use four theoretical models. Among the models selected in chapter 4, the Johnson-Allard-Champoux, Champoux-Sinson models are excluded because they requires more in-put data, which would require further experimental measurements.

The Delany-Bazley model, which is the most commonly used model for the characterization of porous materials, has been added to the models selected in chapter 4. In total, five theoretical models were used to compare with the experimental measurements carried out in a reverberating room and in the Kundt tube.

5.3. Experimental measurements

The INRIM, national institute of metrological research, is a public scientific research center that, for Italy, carries out the functions of the national metrology institute, constituting the guardianship of a large part of metrology, the science of measurement.
INRIM realizes, maintains and develops the national reference standards of the seven basic units of the International System (SI) and the respective derived units. Through these standards, the institute is able to guarantees the reliability of the measures at national level and their comparability at international level.
The fundamental metrological activity is supported by basic and applied research in many fields: materials science, nanosciences, quantum optics, the development of innovative technologies and measuring instruments, and studies on the fundamental constants of physics.
To meet the needs of industry, the Institute has a structure dedicated to innovation and advanced technology, which interact directly with companies and the world of production and provides consulting, calibration and testing services.
INRIM work in support of the National Calibration System, by ensuring the quality of metrological references and taking care of the dissemination of national standards of measurement units [1]. In the INRIM laboratories, the measurements of the flow resistivity, using the acoustic technique on the measurements of the sinusoidal pressure component in a closed volume, and the absorption coefficient, using the Kundt's tube, have been carried out.
The Laboratory of Applied Acoustics is part of DENERG, Energy Department of the Politecnico of Torino. DENERG is the university's reference structure in the cultural areas that deal with the themes of energy and sustainable development with the aim of improving existing energy technologies, promoting new ones and contributing to the rational and conscious use of energy resources. In the Laboratory of Acoustic, there is an anechoic chamber, a 1: 5 scale reverberation room and all the instrument for field measurements [2]. For the measurements of the absorption coefficient of the panels was used the reverberation room, which is the 1: 5 scale reproductions of the one at INRIM institute.

5.3.1. Reverberation room

The dimensions of the reverberation room used for the measurements are 1.53 x 1.56 x 1.20 cm in medium density wood fiber panels, with a thickness of 3.8 cm. On the ceiling, there are hooks to hang the diffusers and holes arranged in a square 4x4 mesh (fig.), to hang the microphones through the bars with a fixed length of 30, 60 or 90 cm [3].

Measurements were made in two source positions and in two microphone configurations for a total of four different room configurations.

The microphones for the first configuration, M1, are in positions: Mic6, with a bar of 60 cm, Mic11, with a bar of 30 cm, and Mic10, with a bar of 30 cm. For the second configuration, the microphones are in position: Mic7, with a bar of 60 cm, Mic15, with a bar of 30 cm, and Mic10, with a bar of 60cm. The source, instead, is positioned in position, S1, in the left corner adjacent to the opening of the room and in position, S2, in the right corner adjacent to the bottom of the room. The source used, which is moved to the two positions, is a dodecahedral source. For each configuration of combined microphones and source, they were made on the same sample three times, without changing the measuring conditions and in a short time, to ensure repeatability of the measurements. In addition, the measurements have been made for all three samples of equal thickness, to guarantee their reproducibility. Was then made an average of the results obtained. The measures were subject to an uncertainty calculated according to ISO / CD 12999-2: 2018. The measurements in the reverberating room were made in accordance with the BS EN ISO 354:2003, as explain in chapter 2.2.1.

5.3.2. Kundt's tube

The measurements in the Kundt tube were carried out as a verification for the results obtained with the reverberation room and to have a direct comparison with the theoretical models.

Only one measurement was made on the 20 mm thick sample.

Being only a verification and having a single measure available, it was not possible to calculate the measurement uncertainty.

The technique used for the measurements in the tube is the one specified in the standard 10534-2, the method of the transfer function with two microphones, explained in detail in paragraph 2.2.2.

5.4. Comparisons between theoretical models and experimental results

The results obtained with the models were compared with the measurements carried out in the reverberation room. To compare the results obtained with the models, with the results of the room it is necessary to integrate the results of the models for all the incidence angles, the models calculate the coefficient of acoustic absorption at normal-incidence, while the reverberation room calculates it in the diffuse field. To convert the models from normal incidence to diffuse field, it was used the method in the UNI EN ISO 10534.

Consider the selected calculation models one by one and comparing them with the measurements in the room, one notices that there is not a model that has a good

correspondence with the experimental measurements, even if both parts show a good sound-absorbing capacity at high frequencies. The Delany-Bazley model like Delany-Bazley-Miki model have a correspondence with the measurements in the room between 3150 and 5000 Hz. The Miki generalization model finds a correspondence with the measurements between 315 and 1250 Hz and 3150 Hz. The Hamet-Berengier model coincides for the frequencies 315-630 Hz. Voronina coincides between 150-200 Hz and 4000-5000 Hz. Given the lack of correspondence between the measurements in the room and the models, it was decided to make a measurement with the Kundt tube for further verification. The results obtained with the Kundt tube have also been transformed into a diffuse field. As for the models also the results of the tube did not give a direct comparison with the results obtained with the camera in fact, the results coincide only at 150-250 Hz and 3150-5000 Hz.
The results of the models were also compared with the results obtained with the Kundt tube. In this case, the models follow better the gait of the curve obtained with the tube measurements. The models that best compare with the tube results are Hamet-Berengier and Miki generalization model.

5.5. Bibliography

[1] "Missione | INRiM." [Online]. Available: https://www.inrim.it/lente/chi-siamo/missione. [Accessed: 15-Nov-2018].

[2] "DENERG - Dipartimento Energia." [Online]. Available: https://www.polito.it/ricerca/dipartimenti/denerg/. [Accessed: 15-Nov-2018].

[3] A. Gerbotto, "Caratterizzazione di una camera riverberante in scala," Politecnico di Torino, 2016.

6. Conclusion

6.1. Improvement

By comparing the data obtained through the theoretical models and the experimental measurements made, it is possible conclude that, the material taken into account, is able to absorb the sound only at high frequencies. Through the data collected with the measures and previous research on cementitious materials, it was possible to propose changes to the testing sample to improve its sound-absorbing performance.

6.1.1. Thickness

As already seen in paragraph 3.3.3. the thickness is one of the major parameters that affects the sound absorption capacity of a material. With the increase in the thickness of the material, a shift of the sound absorption coefficient spectrum towards lower frequencies can be noted. As said previously, in chapter 5.1., the tested sample have three different thicknesses: 20 mm, 40 mm and 60 mm. In the reverberation room, the panels of the three different thicknesses were tested to test how the thickness could influence the sound absorbing capacities. As is possible to note from fig.6.1.1.1. on our sample there is not a real translation of the curve but it is noticed how increasing the thickness the sample is able to absorb the sound already at lower frequencies. If with a thickness of 20 mm it is possible to notice an increase in absorption coefficient only from 2500 Hz, increasing the thickness at 40 mm, it is noted that this increase is already present from 800 Hz, and increasing the thickness up to 60 mm the increase is it already has from 630 Hz. From these results it is possible conclude that, in order to have greater sound absorbing capacities even at lower frequencies, it is sufficient to increase the thickness of the material.

6.1.2. Position

Considering a stationary wave, of whatever wavelength λ, the maximum absorption will be where the particle velocity is maximum. in order to place a sound-absorbing material on a surface it is therefore necessary to consider that, the first point corresponding to the maximum speed is located at a distance of $d=\lambda/4$ from the wall, and the points after each odd multiple of $\lambda/4$ moving away from the wall. As you can see from the fig.6.1.2.1. in an ideal situation, the trend of the absorption coefficient according to the normalized distance $4d/\lambda$, will have a trend of selective absorption with the maxima at distance $d=n(\lambda/4)$, n is an odd integer. Then, by placing an absorbent material of thickness d against a wall, the material will absorb all the wavelengths with the first maximum of vibration at a distance from the wall lower than the thickness of the material layer, that is $\lambda<4d$. By spacing the absorbent material from the wall, thus creating an air gap, of a distance d', the acoustic waves with $\lambda<4(d+d')$ will be absorbed [1]. Therefore, as already noted for the thickness, the frequency for which the absorption coefficient begins assume significant values depends on the distance at which the material is placed. In this regard, it has been tried to make measurements in the reverberation room placing the 20 mm thick panel on a 50 mm wooden frame, thus creating an air gap. Comparing the results of the 20 mm thick panel with those of the panel + air gap, it is noted that with the help of the gap, the panel has an uplifting of the absorption coefficient values already at 500 Hz.

6.1.3. Aggregate

The most drastic change that can be applied, to modify the sound absorbing performances, is to change the aggregate. As already seen in chapter 3.3.2. changing the aggregate it is possible to modify the sound absorbing capacities of the material. Changing the aggregate not only involves a change in the design of the material but changes all the parameters of the material. Several articles have been examined regarding the use of different types of aggregate.

Vasina et al. [2] uses expanded clay as an aggregate, of different sizes starting from a smaller one of 3.5 mm in diameter, increasing to 6.5 mm, then to 8.5 mm and at the end 12 mm. From this study it is noted that the size of the aggregate does not influence the frequency at the maximum absorption coefficient, which remains unchanged, but the increase in the aggregate size reduces the value of the maximum of the absorption coefficient.

6.2. Concrete is a good sound absorption?