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CONSOLIDATION EFFECTS ON THE ACOUSTIC PROPERTIES OF GRANULAR MIXES

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1. INTRODUCTION

Sound absorbing materials are widely used to modify the sound field in both indoor and outdoor situations. Indoors they are used to improve the acoustics of working, living and performance places. Outdoors they are used to modify the effect of reflection on the noise environment, for example, by application on the surface of noise barriers. Many acoustic absorbers are produced in the form of granular or fibrous materials with high percentage of open pores.

In recent years the automotive industry has become a source of raw materials for the production of porous absorbers. The industry uses an increasing quantity of elastomeric and polymeric materials. When a vehicle reaches the end of its life a substantial proportion of it is disposed of as plastic or rubber waste. There is a tendency to re-use waste in the production process and make any future products fully recyclable. As an example, Ford are now producing vehicles which incorporate up to 25% of recycled waste. In their new car, the Ford Focus, textile and plastic waste is incorporated in heater/air-conditioning equipment, fuse boxes and sound absorbing components (see ref. [1]). Used tyres constitute a great proportion of total automotive waste. The cost of recycling of tyres is high. In the UK the typical cost to recycle a super-single tyre is as high as £7. In most cases, this waste is reduced to granulate and then separated. Possible applications of this waste are limited. At the same time, the relatively high open porosity of the granulated rubber suggests that this material can possess high values of the acoustic absorption in a broad frequency band. Such a material can be re-used in noise control applications. In its consolidated form this material can also provide good vibration damping and acoustic insulation. Consolidated materials are easy to transport and to install. These materials do not require special protection covers and can be produced in a variety of shapes.

Previous works [2-4] indicate that the acoustic performance of porous materials, which are consolidated from granulated rubber waste, largely depend upon the size of granules in the mix and the parameters of the consolidation process. Preliminary studies [2] suggest that the application of a binder results in the reduced porosity and increased flow resistivity, which adversely affects the overall acoustic performance of the consolidated granular mix.

The purpose of this work is to investigate more systematically the physical relations between the non-acoustic parameters of loose and consolidated granular rubber mixes, parameters of the consolidation process and the acoustic performance of these materials in their consolidated form.

2. METHODOLOGY

A set of experiments, which is described in this section has been carried out on several loose and consolidated samples of granular rubber mixes. Most rubber granular mixes are constituted of granules which vary in size considerably in the range of up to 6 mm. To produce a material with high percentage of open pores it is necessary to sieve the mix to remove very small fractions. Some published works [2,4] suggests that there should be an optimal statistical distribution of granule sizes in the mix which can provide a porous material with the highest possible values of the acoustic absorption in a broad frequency range.

In this study the non-acoustic and acoustic properties of mixes of four different granule sizes have been prepared and investigated. The sizes of these mixes are: 0.71 - 1.0 mm, 1.0 - 1.4 mm, 1.4 - 2.0

mm and > 2.0 mm. The loose materials have been consolidated using a laboratory press and a polyurethane binder. The compaction ratio (BC) and the binder concentration (BC) have been carefully controlled. The following properties have been investigated: average pore size, *b*, standard deviation of the pore size, σ, flow resistivity, *R*, porosity, Ω, characteristic and surface impedance, propagation constant and absorption coefficient.

The statistical parameters of pore size distribution have been measured using the water suction method described in ref. [5]. Because of small specific density of rubber, it is impractical to apply this method to loose rubber granulates, therefore this method has only been used with consolidated materials. The porosity of loose granular mixes has been calculated as $\Omega = 1 - \rho_m / \rho_r$, where ρ_m and ρ_r are the density of the mix and the density of the granules, respectively. The flow resistivity of all the materials has been measured using the method detailed in ref. [6]. The acoustic properties of these materials have been measured using a 2-microphone impedance tube in the frequency range of 100 - 6500 Hz. The impedance of each sample has been measured with and without an air gap, which enabled to deduce the characteristic impedance and propagation constant.

3. NON-ACOUSTIC PROPERTIES

It has already been mentioned that the porosity of many loose rubber granular materials is relatively high. The value of the porosity seems to be independent from the average size of the granules in the mix. Measurements suggest that the most typical value of the porosity for a loose mix is in the region of 60%. During the compaction process the porosity can change considerably as shown in Figure 1, where the measured porosity is plotted against the mean grain size for different compaction ratios. Here the compaction ratio corresponds to the percentage reduction of the layer depth due to the consolidation pressure during the compaction process (see the definition for CR provided below). It is evident from Figure 1 that, although the porosity reduces with increased compaction, its value is affected very little by the size of granules used to produce the material (porosity fluctuations < 3%). Assuming that the binder does not influence the packing conditions of the materials, this is an expected result, since the granules are of similar shape throughout their size distribution.

Figure 2 illustrates the dependence of the porosity on the compaction ratio. Although the experimental data suggests that the decrease in porosity is approximately linear, the theoretical relation between the porosity and the reduction in volume caused by compaction is more complex. It is easy to verify that the porosity of the consolidated material is predicted as following expression

$$\Omega_c = (\Omega_o - \nu)(1 - \nu)^{-1}, \quad (1)$$

where Ω_o is the porosity of the loose granular mix, $\nu = \Delta V / V_o$ is the compaction ratio (CR = 100%ν), ΔV is the reduction of the total pore volume and V_o is the original volume of the mix, which correspond to CR = 0% and the chosen binder concentration. It can be assumed here that the reduction in volume caused by compaction will be equal to the reduction in the total pore volume in the sample. It is clear from the theoretical result, that for low compactions, i.e. below 30%, an increase in the compaction ratio will produce an approximately liner reduction in porosity, which is supported by the experimental results. Figure 2 suggests that the porosity of the consolidated material reduces by more than 50% of the original value, for compactions greater than 40%. This almost certainly, should have an adverse effect on the acoustic properties of the material, as will be shown later in this paper.

The effect of the binder concentration on the value of the porosity is shown in Figure 3. The presented data are obtained from repeated measurements on samples of consolidated rubber granulates with full distribution of sizes and fixed compaction ratio of 25%. The density of the binder is ρ_b = 1170 kg/m^3, whereas the density of rubber is ρ_r = 1050 kg/m^3 The figure suggests that, as expected, the relationship between the porosity and binder concentration is close to linear. It is easy to verify that the theoretical value of porosity can be predicted by the following expression

$$\Omega_b = \Omega_o - \beta\chi(1 - \Omega_o), \quad (2)$$

In this expression Ω_o is the porosity of the loose mix in the chosen compaction state (in this case CR = 25%); $\chi = \rho_r / \rho_b$ is the densities ratio and $\beta = m_b / m_r$ is the mass proportion of the binder (BC = 100%β). m_b and m_r are the mass of binder and rubber granules in the sample, respectively. It is assumed that the mass of rubber is considerably higher than that of the air in the pores.

An important parameter for an acoustic porous material is the mean pore size, which is related to the flow resistivity of the mix. It is controlled by the mean grain size, the standard deviation in the grain size and the shape of granules. The relation between the mean grain size and the mean pore size has been measured for different compaction ratios and the results are shown in Figure 4. The presented dependencies show trends, which are similar for CR > 0%. As expected, the mean pore size is reduced for the increased compaction ratios and it almost linearly depends on the mean grain size. In the case of granular mix with very a small compaction ratio, the dependence is more complex. In this case, the mean pore size is more rapidly reduced for the reduced mean grain size. This can be explained by the fact that the pore size for materials with small grains becomes comparable to the viscous skin depth of the binder, resulting in additional reduction of the mean pore size.

It can be observed from Figure 4 that the reduction in the mean pore size is maximum for smaller compaction ratios, 0 < CR < 15%. The smaller compaction ratios have a greater effect on the mean pore size in materials with larger grains. It may be suggested that the larger pores experience the larger specific volume reduction during the compaction process, because they are easier to compress. Therefore, the application of even small pressures can considerably reduce the mean pore size of a porous sample. It can also be noted that the graphs approach linearity in the case of materials produced under greater pressures. This can be attributed to the compaction aiding the spread of binder through the material, causing excess binder from smaller pores to be squeezed into adjoining larger pores. In this process, the decrease of the mean pore size is due to the significant compression of larger pores, whereas the increase in the relative proportion of larger pores is due to the binder effects within the structure.

Figure 5 shows the mean pore size for samples made with different binder concentrations. As expected, the mean pore size decreases with increased binder concentration close to linearity. Mixes with all grain sizes (up to 6 mm) have been used in this investigation. The experimental data suggest that doubling the binder concentration results in approximately 15% reduction in the pore size.

The flow resistivity of porous materials largely determines their acoustic performance. This quantity is routinely measured using apparatus described in [6]. Figure 6 shows the flow resistivity as a function of particle size and compaction ratio. It can be noticed that the value of the flow resistivity is more sensitive to smaller particle sizes, because it is proportional to the internal surface area. The latter, in its turn, is inversely proportional to the squared particle size, which can explain the results.

It can be suggested that although small compaction ratios considerably affect the size of pores (see Figure 4), they do not necessarily result in any significant variation of the flow resistivity. This phenomenon needs further investigation. It is possible to suggest that the compaction process alters the geometry of the porous structure. In this case, the shape parameter, s, in the well-known relation $R = s\eta q^2 / (\Omega_c b^2)$, becomes dependent upon the compaction ratio (e.g. s = 3 for slit-like pores, s = 8 for circular pores and s = 80 for equilateral triangles). Here η is the dynamic viscosity of air and q^2 is the tortousity. This parameter can be investigated in detail using methods of optical analysis which are routinely used in geophysics (e.g. [7]).

4. ACOUSTIC PROPERTIES

Acoustic measurements provided results for normal incidence surface impedance, absorption coefficient, characteristic impedance and propagation constant. For brevity, only absorption coefficient data is provided in this paper.

Figure 7 shows the absorption coefficient spectra for consolidated materials with variable mean grain size and fixed values of CR = 15% and BC = 15%. The results suggest that the value of the absorption coefficient reduces with the increased mean particle size. However, the experiments with more finer mixes, which are reported in ref. [2], suggest that 0.71 – 1.0 mm mix yields the optimal acoustic performance, as any further reduction in the particle size results in a considerable loss of the acoustic performance (see [2]). This is attributable to binder effects, where the binder viscous skin depth becomes comparable to the pore size.

Figure 8 shows the absorption coefficient spectra for consolidated materials with variable compaction ratio and fixed binder concentration, BC = 15%. The results suggest that that there should be an optimal value of the compaction ratio in the area of 25%. A considerable shift of the resonance towards low frequencies can be clearly observed for increased compaction ratios. This shift is the result of the increased tortuosity, which value is provided in the brackets behind the value for a compaction ratio in the figure legend.

Figure 9 shows the absorption coefficient spectra for consolidated materials with variable binder concentration and fixed compaction ratio, CR = 25%. Mixes with all grain sizes (up to 6 mm) have been used in this investigation. It is clear that the increasing binder concentration results in lower values of the absorption due to the reduce porosity and increased flow resistivity. There are ranges of binder concentration 10 < BC < 15% and 20 < BC < 25%, where the absorption coefficient is less sensitive to the variation in this parameter. An increase in the binder concentration from 15% to 20% results in noticeable reduction of the absorption coefficient values, throughout the spectrum.

The results suggest that similar increases in the binder concentration may not necessarily result in equal reduction in the absorption coefficient. For example, the absorption coefficient is less sensitive to the variation in the binder concentration in the range of 10 – 15% and 20-25%, whereas there is a noticeable reduction in the absorption values in the range of 15 – 20%. This result is important to establish the optimal balance between the structural and acoustic performance of consolidated granular mixes.

5. CONCLUSIONS

Acoustic measurements performed on non-spherical granular mixtures with different states of consolidation suggest that their acoustic performance can be related to that measured in the loose granular mixtures and mixes with very small compaction ratios. It was found that such predictions depend greatly on the knowledge of several non-acoustic parameters, namely: porosity, mean pore size, flow resistivity and tortuosity. The effects of varying quantities of binder, and the applied packing pressure on these parameters have been investigated for a number of samples of rubber crumb having different particle size. This enables a quantitative comparison between the acoustic properties of media in different states of consolidation. These results can lay down a scientific methodology for the design of porous recycled materials with optimal acoustic and structural performance for noise control and architectural acoustic applications. The experimental results are particularly useful to investigate the validity of theoretical models for sound propagation in porous media with pore size distributions.

6. REFERENCES

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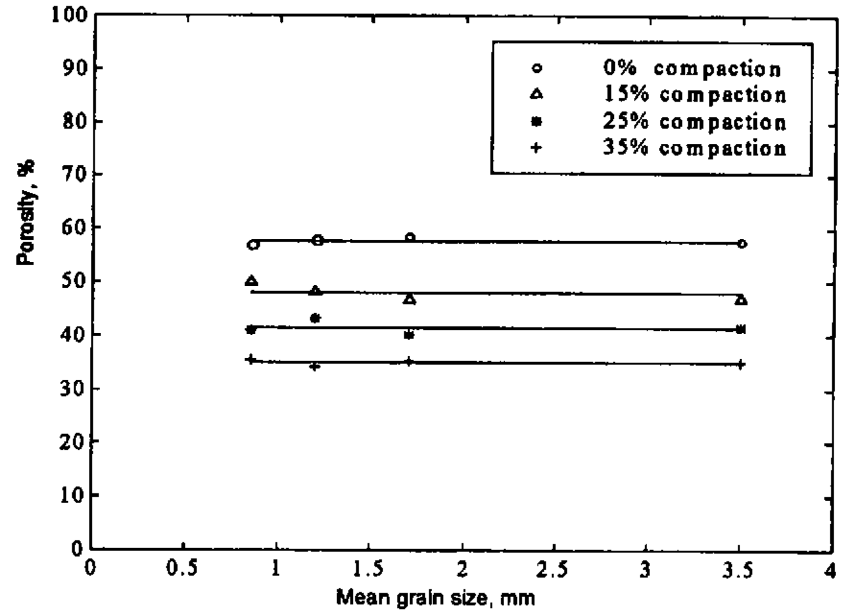

Figure 1. Porosity as a function of the grain size for consolidated samples of granular rubber mixes.

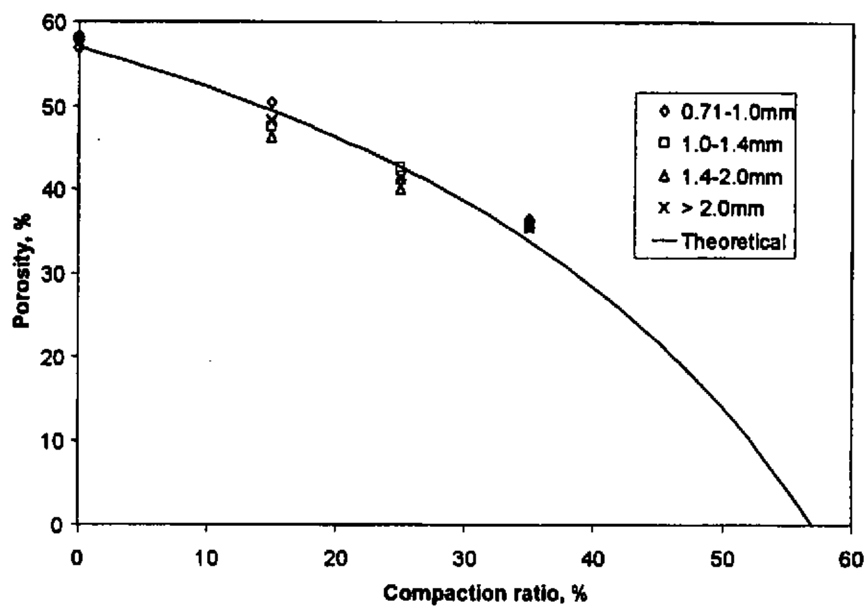

Figure 2. Porosity as a function of the compaction ratio for consolidated samples of granulated rubber with different grain size. Solid line corresponds to the theoretical result.

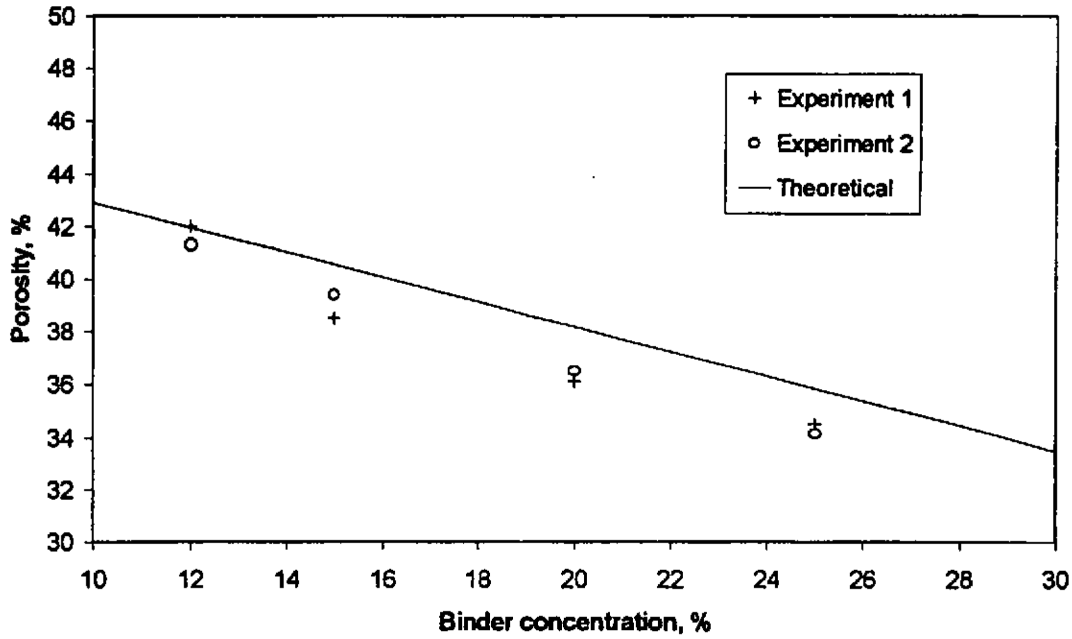

Figure 3. Porosity as a function of binder concentration. All grain sizes.

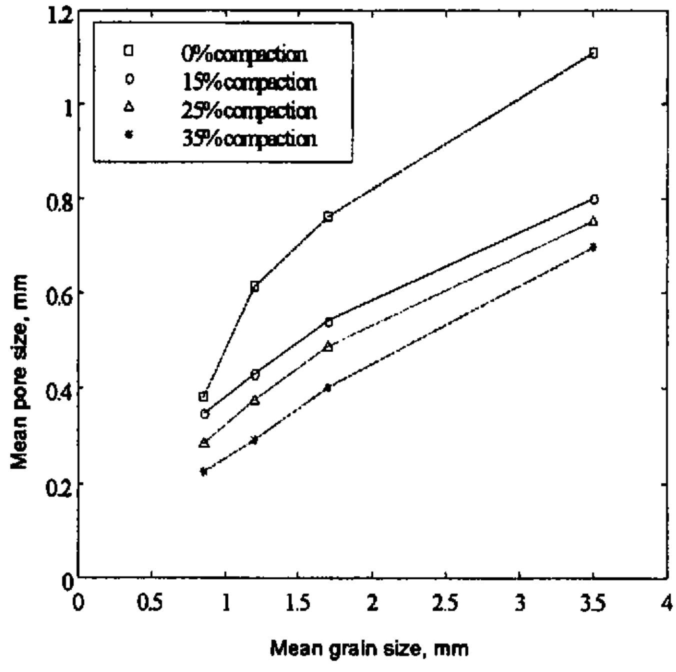

Figure 4. Mean pore size as a function of mean grain size for consolidated granular rubber mixes.

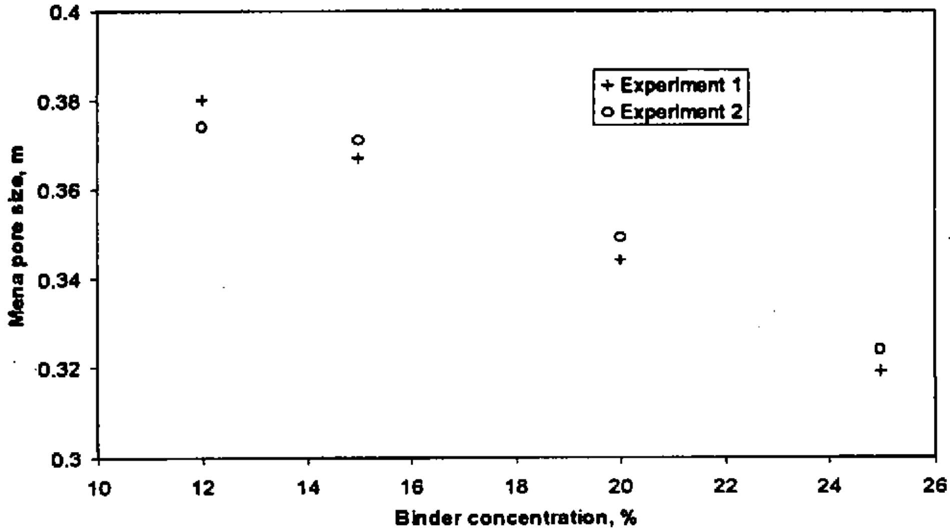

Figure 5. Mean pore size as a function of binder concentration. All grain sizes.

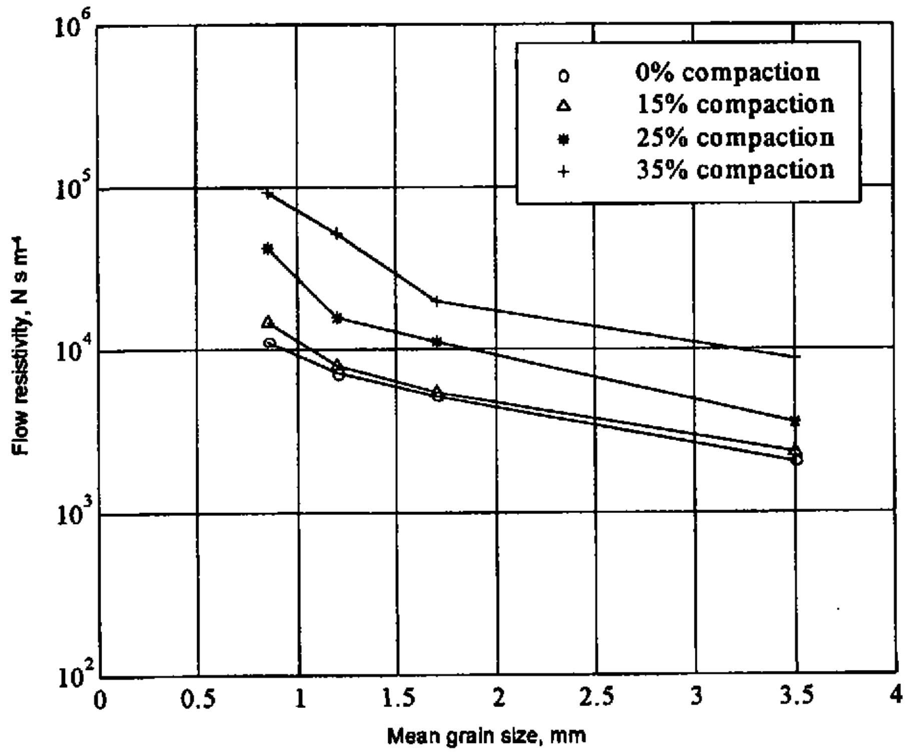

Figure 6. Flow resistivity as a function of mean grain size. BC = 15%.

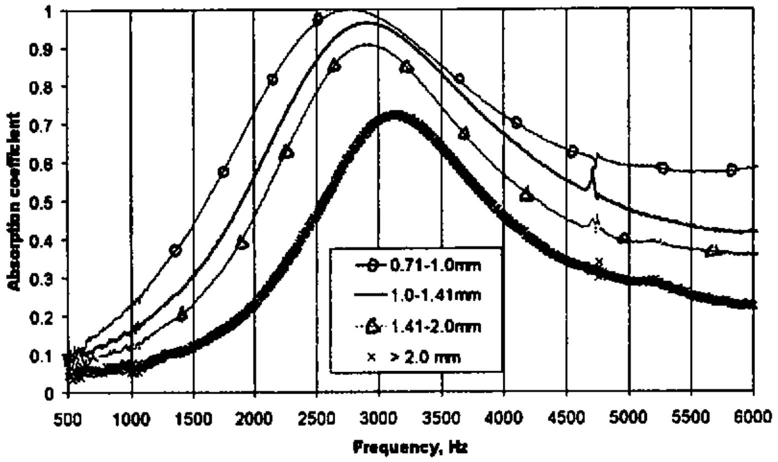

Figure 7. The effect of the grain size on the plane wave absorption coefficient. BC = 15%, CR = 15%.

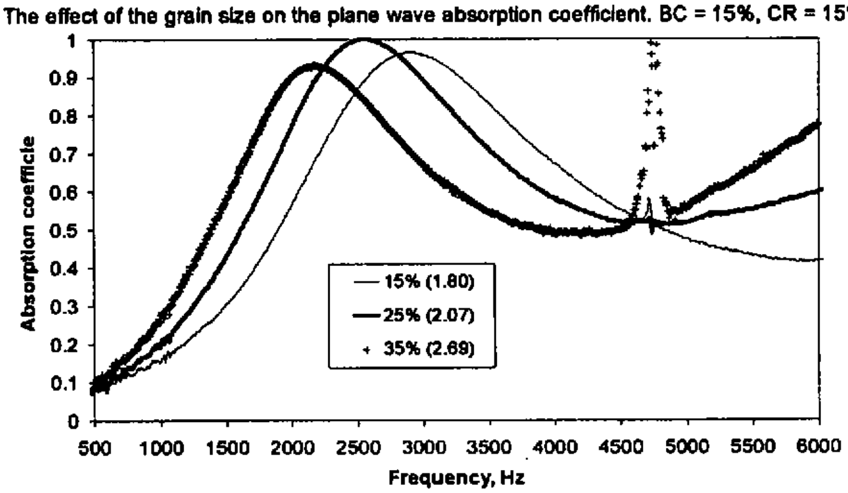

Figure 8. The effect of the compaction ratio on the plane wave absorption coefficient. BC = 15%, 1.0 - 1.41 mm grains.

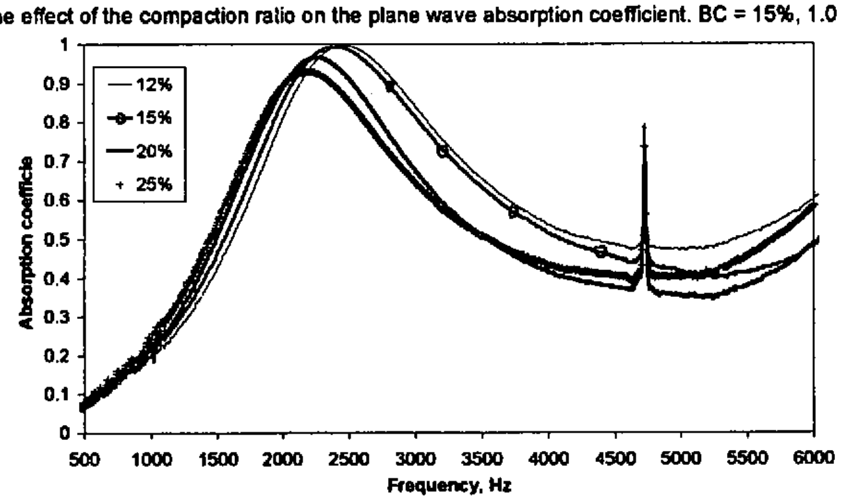

Figure 9. The effect of the binder concentration on the plane wave absorption coefficient. CR = 25%. All grain sizes.