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EXPERIMENTAL EVALUATION AND THEORETICAL REPRESENTATION OF CONSOLIDATED GRANULAR MATERIALS FOR NOISE CONTROL.

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ABSTRACT

This work aims to study the behaviour of consolidated granular materials in the sound absorption for noise control applications. The sound absorption was studied for normal incidence in samples with different thickness, grain size and quantity of cement. Experimental techniques were used to obtain the surface impedance, characteristic impedance and the wave number of the material. In addition to the experimental techniques, an inverse method based on the use of a genetic algorithm was applied to obtain 4 macroscopic parameters (porosity, flow resistivity, tortuosity and standard deviation of pore size) that represent the material through the theoretical model of Horoshenkov-Swift.

RESUMO

O presente trabalho tem como objetivo estudar o comportamento da absorção sonora de materiais granulares consolidados, para aplicações em controle de ruído. Estudou-se a absorção sonora para incidência normal em amostras com diferentes espesuras, granulometrias e quantidade de cimento. Técnicas experimentais são usadas para obtenção da impedância de superfície, impedância característica e número de onda do material. Além de técnicas experimentais, um método inverso baseado num algoritmo genético foi utilzado para obtenção dos quatro parâmetros macroscópicos (porosidade, resistividade ao fluxo de ar, tortuosidade e desvio padrão do tamanho do poro) capazes de representar os materiais estudados através do modelo teórico de Horoshenkov-Swift.

1. INTRODUCTION

In the 19th century, Rayleigh began the study of the acoustic behavior of porous materials in his classic work [1]. Since then, porous materials have been widely used in passive noise control and indoor acoustic treatment. Porous materials are composed of two phases, one solid and another fluid interstitial to the pores, and the dissipation of the sound energy occurs through the interaction between the two phases [2].

Currently, porous materials, such as fibers and foams, are commonly used in commercial solutions because of their excellent sound absorption at high frequencies. However, for exterior applications these materials require environmental protection and structural reinforcement [3]. In 2000, Magrini and Ricciardi [4] proposed the use of expanded clay in the production of porous concrete, and since then several studies with different applications have been performed.

This work aims to study the sound absorption behavior of consolidated cementitious granular materials with different thickness, grain size and quantity of cement. For this study, 24 samples were built using 3 different mixtures, which will be presented in the next Section. Experimental techniques and theoretical models were used for material characterization and sound absorption representation. The grain size characterization was performed using the sieving method. The acoustical characterization was based in two experimental methods, where the surface impedance, characteristic impedance and wave number were measured.

On the other hand, the Horoshenkov-Swift model was chosen for analytical representation of the studied materials. Four macroscopic parameters are necessary in this model: the flow resistivity, the open porosity, the tortuosity and the standard deviation of the porous size. The open porosity is obtained experimentally, while the other parameters are obtained through an inverse method based on the use of a genetic algorithm.

2. NON-ACOUSTIC PROPERTIES

Three grain sizes of expanded clay were selected in the production of samples, using different component mixtures (incorporating aggregate, cement and water – A/C/W), so as to study the influence of grain size, quantity of cement and material thickness on the sound absorption.

The used expanded clay granulates are presented in Figure 1, classified through the commercial names: 0-2, 2-4 and 3-8F. To analyze the size distribution of these aggregates, an experimental characterization described by NP EN 993-1:2000 [5] was proposed, using the sieving method. Figure 2 shows the experimental curves of grain size distribution, where the aggregate denominated 3-8F has the highest grain and 0-2 the smallest. As can be observed, the grain size distribution is relatively compact for the three cases.

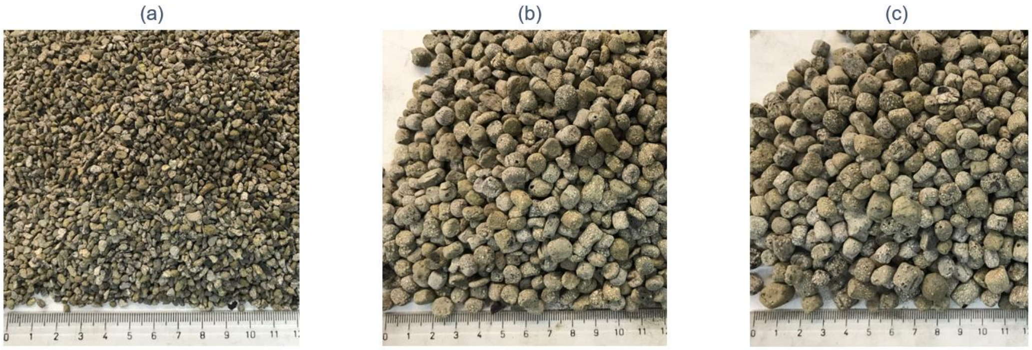

Figure 1. Morphology of the three sizes of expanded clay studied: (a) 0-2, (b) 2-4 and (c) 3-8F.

After the grain size characterization, three sets of consolidated porous concrete were built. The first mixture had 48.48% of aggregate, 34.32% of cement and 17.20% water, however this mixture was not performed for samples with grain size 0-2. The second mixture had 43.96% of aggregate, 37.36% of cement and 18.68% of water. While the third mixture is produced only for the grain size 0-2 and is composed of 40.17% of aggregate, 38.89% of cement and 19.97% of water.

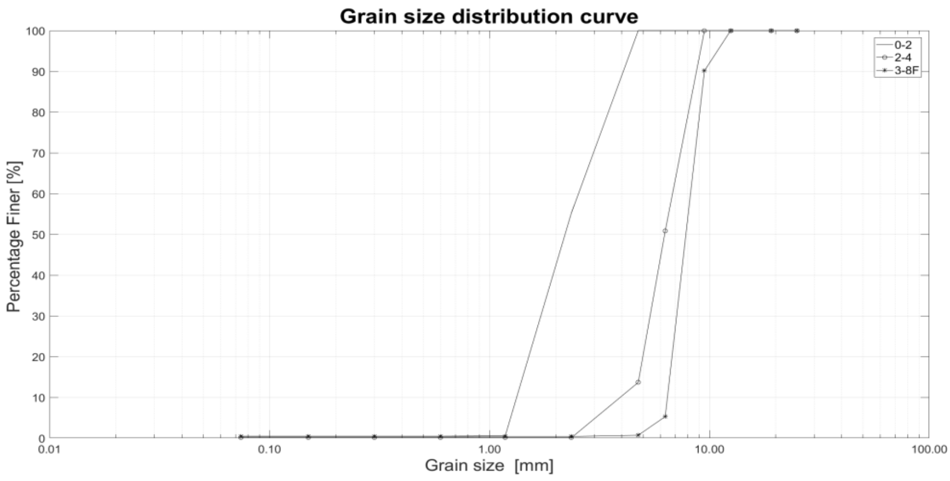

Figure 2. Grain size experimental evaluation.

Table 1 shows the mixtures and specifications of the produced samples. Two samples were made for each mixture and thickness (4 and 6 centimeters), and the volumetric mass density of each sample were also presented.

Table 1. Granulation mixtures preparation data.

Granular mixture	A/C/W* (%)	Grain size (mm)	Thickness (cm)	Sample	Volumetric mass density (kg/m^3)
Mixture 1	48.48/34.32/17.20	2-4	4	1	148.58

				2	144.52
			6	1	149.94
				2	159.14
		3-8F	4	1	146.15
				2	147.77
			6	1	125.04
				2	132.61
Mixture 2	43.96/37.36/18.68	0-2	4	1	163.19
				2	164.82
			6	1	168.34
				2	159.68
		2-4	4	1	160.76
				2	173.75
			6	1	178.09
				2	177.54
		3-8F	4	1	166.45
				2	155.08
			6	1	172.13
				2	162.93
Mixture 3	40.17/38.89/19.92	0-2	4	1	199.73
				2	208.67
			6	1	202.98
				2	208.94

*A/C/W indicates the percentage of Aggregate, Cement and Water proportions of each mixture, respectively.

3. METHODOLOGY

3.1 Experimental setup

Two experimental techniques were used to characterize the absorbent behavior for normal incidence of the produced samples. The two methods allow an evaluation of the sound absorption based on the use of an impedance tube and the transfer function between two microphones. The impedance tube used has a circular cross-section of 10.1 cm, where the cut-off frequency is approximately 1600 Hz. A random excitation is provided to the loudspeaker from the analyzer OR 34 Compact Analyser and the sound pressure is measured using two microphones B&K Type 4188 ½ in and the data post-processed in Matlab.

The first experimental method used is based on the standard ISO 10534-2 [6]. This procedure allows obtaining the surface impedance Z_s for normal incidence of the sample tested. The Z_s is calculated through Equation (1), where ρ_0 is the air density and c_0 is the propagation speed of sound in air.

$$Z_s = \rho_0 c_0 \frac{(1+R)}{(1-R)}. \tag{1}$$

The reflection coefficient, *R,* is obtained through Equation (2), where S_i is the distance between the two microphones, x_i is the distance between the sample and the microphone farther from the loudspeaker, $\tilde{k}$ is the complex wave number and H^*_{12} is the transfer function between the two microphones, incorporating the phase correction described in the standard,

$$R = \frac{H^*_{12} - e^{-2j\,\tilde{k}\,s_i}}{e^{j\,\tilde{k}\,s_i} - H^*_{12}} e^{2j\,\tilde{k}\,x_i}. \tag{2}$$

The second experimental method used is the Utsuno Method [7]. This method is based on two measurements with the same sample, where both measurements use the methodology of the transfer function between two microphones. The first measurement has a rigid termination behind the sample, while the second measurement has an air cavity between the sample and the rigid termination. The Utsuno Method makes it possible to obtain the characteristic impedance Z_c and the complex wave number γ of the material, respectively through Equations (3) and (4),

$$Z_c = \sqrt{\frac{Z_s Z_s'(Z_1 - Z_1') - Z_1 Z_1{}'(Z_s - Z_s{}')}{(Z_1 - Z_1') - (Z_s - Z_s{}')}} \tag{3}$$

$$\gamma = \frac{\mathrm{j}}{2d_1} \ln\left(\frac{Z_s' + Z_\mathrm{c} Z_s' - Z_\mathrm{c}}{Z_1' - Z_\mathrm{c} Z_1' + Z_\mathrm{c}}\right) \tag{4}$$

where Z_s is the surface impedance measured with the rigid termination, while Z_s' is the surface impedance of the sample measured with presence of the air cavity. Z_1 and Z_1' denote the specific acoustic impedance of the air cavity, represented respectively by the following equations, where *D* is the depth of the air cavity and *d₁* is the thickness of the porous material,

$$Z_1 = -j\rho_0 c_0 cot(\gamma D). \tag{5}$$

$$Z_1{}' = -\mathrm{j}\rho_0 c_0 \cot(\gamma D'). \tag{6}$$

3.2 Horoshenkov and Swift Model

Several theoretical models are used to predict the acoustic absorption of porous materials. In this work, the model of Horoshenkov and Swift [8] was used. This model allows to estimate and to represent the behavior of the sound absorption of the samples of consolidated granular materials.

The present model considers four macroscopic parameters to represent the behavior of the studied materials, namely, flow resistivity σ, open porosity ϕ, tortuosity α_∞ and the standard deviation of the porous size σ_p. This model was derived from the previous properties for rigid frame granular media with a log-normal pore size distribution. The behavior of the material can be represented by the complex density ρ, and the compressibility C, calculated using the following equations:

$$\rho(\omega) = \frac{\alpha_\infty}{\phi}\left(\rho_0 - \frac{\phi\sigma}{\mathrm{j}\omega\alpha_\infty \tilde{\mathrm{F}}(\omega)}\right), \tag{7}$$

$$C(\omega) = \frac{\phi}{\gamma \mathrm{P}_0}\left(\gamma - \frac{\rho_0 \alpha_\infty (\gamma - 1)}{\phi\rho(\mathrm{N}_{\mathrm{pr}}\omega)}\right) \tag{8}$$

where γ is the ratio of specific heats, P_0 is the atmospheric pressure and N_{pr} is the Prandtl number; $\tilde{F}$ is the viscosity correction function, which can be presented in the form of Padé approximation as:

$$\tilde{F}(\omega) = \frac{1 + a_1\epsilon + a_2\epsilon^2}{1 + b_1\epsilon}, \tag{9}$$

where $a_1 = \theta_1/\theta_2$, $a_2 = \theta_1$ and $b_1 = a_1$. Using the circular pore geometry assumption $\theta_1 = \frac{4}{3}\mathrm{e}^{4\xi} - 1$ and $\theta_2 = \frac{\mathrm{e}^{3\xi/2}}{\sqrt{2}}$, where $\xi\left(\sigma_p \ln(2)\right)^2$ and $\epsilon = \sqrt{-j\omega\rho_0\alpha_\infty/(\sigma\phi)}$ is a dimensionless parameter.

3.3 Macroscopic parameters characterization

To determine the four macroscopic parameters required to represent the materials studied through the Horoshenkov and Swift model two methodologies were used. The open porosity was experimentally determined, calculated from $\phi = V_f/V_t$, where V_f is the volume of fluid-space and V_t is the volume of the material sample. The volume of fluid-space determined by $V_f = (M_{\text{sat}} - M_{\text{dry}})/\rho_{\text{water}}$, where M_{sat} is the mass of the sample saturated with water, M_{dry} is the mass of the sample and ρ_{water} is the water density.

The other three parameters, flow resistivity, tortuosity and the standard deviation of the porous size, were obtained through the application of an inverse method. This method is based on the use of a genetic algorithm [9], where the objective function is described in the Equation (10), with $\tilde{Z}_{\text{ana}}$ being the analytical surface impedance and $\tilde{Z}_{\text{exp}}$ is the experimental surface impedance,

$$obj(\omega) = \sum_{i=1}^{nf}\left(Re\left[\tilde{Z}_{ana} - \tilde{Z}_{exp}\right]\right)^2 + \sum_{i=1}^{nf}\left(Im\left[\tilde{Z}_{ana} - \tilde{Z}_{exp}\right]\right)^2 . \qquad (10)$$

4. RESULTS

4.1 Acoustic properties

This section presents the experimental characterization results, according to ISO 10534-2, of the samples presented in Table 1. The aim is to analyse the influence of the grain size, thickness and quantity of cement on sound absorption.

Figure 3 shows a comparison of the absorption coefficient variation according to the increase of the thickness and to the change in the grain size, for samples denominated as "2" of the mixture 2 (see Table 1). Figures 3(a), 3(b) and 3(c) illustrate the influence of sample thickness on sound absorption comparing samples with 4 and 6 cm. Figure 3(d) presents the influence of grain size, comparing three different grain sizes, for samples with 4 cm thickness.

In Figures 3(a), 3(b) and 3(c), the existence of a pattern in the variation of the sound absorption coefficient can be observed, where the increase of the thickness provides a shift in the absorption curve towards the low frequencies. This effect occurs for all tested samples, regardless of the quantity of cement and grain size present in the samples.

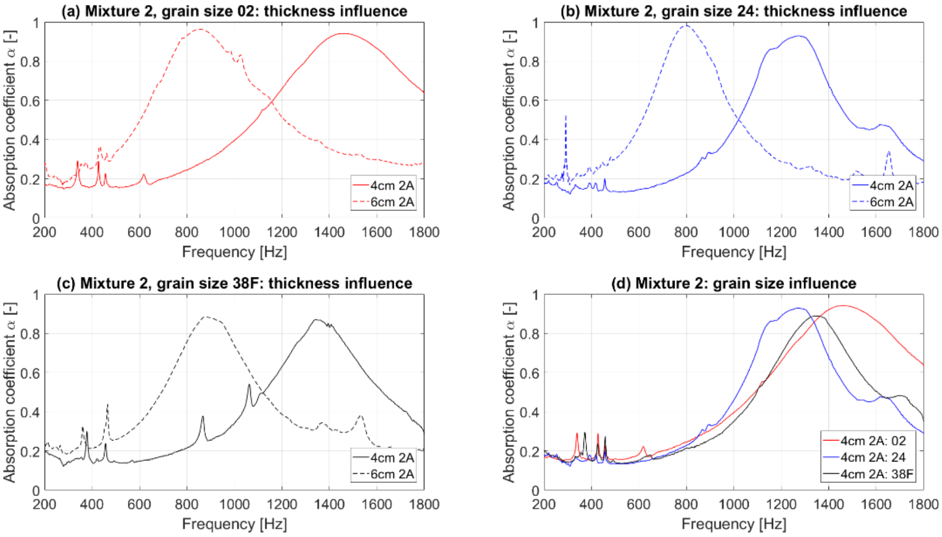

Figure 3. Comparison of the absorption coefficient variation according to increase of the thickness and change of the grain size, for samples 2 of the mixture two, with 4 and 6 cm.

In Figure 3(d), it is noted that the sample with smaller grain size, denominated 02, has a higher absorption coefficient in terms of frequency when compared with the samples of grain sizes 24 and 38F. The sample with 4 cm has an absorption coefficient higher than 0.8 between approximately 1300 and 1650 Hz. Samples with the same thickness and grain sizes 24 and 38F have an equivalent absorption coefficient between approximately 1120 and 1360 Hz and 1300 and 1430 Hz, respectively.

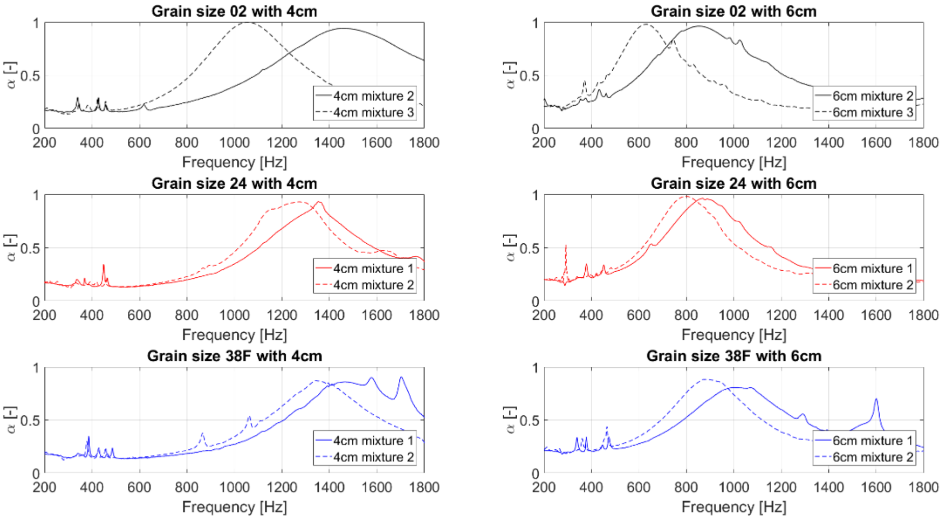

Figure 4. Comparison of the absorption coefficient variation according to increase the quantity of cement in the samples with same grain size and thickness.

The influence of the variation of the quantity of cement in the sound absorption is presented in

Figure 4, where the samples of different mixtures with the same thickness and grain size are compared. It is noted that increasing the quantity of cement provides a shift of the absorption coefficient to lower frequencies, as similarly observed with increasing thickness. Note that samples with grain size 02 and 4 cm show the greatest variation. One can perceive a lateral narrowing in the absorption coefficient in terms of frequency, and shift of the absorption peak to lower frequencies with increasing quantity of cement.

4.2 Macroscopic parameters

This section presents the macroscopic parameters that allow the behavior representation of the studied materials through the Horoshenkov and Swift model. As described in Section 3.3, an experimental technique was used to obtain the open porosity, while the other three macroscopic parameters (flow resistivity, open porosity, tortuosity and the standard deviation of the porous size) were obtained using the inverse method presented in Equation (10).

The macroscopic parameters that best represent the characterized samples are presented om Table 2. In order to verify the performed inverse approximation, where the adjustment is based on the surface impedance, a comparison of the characteristic impedance and wave number was performed. Through these two acoustic characteristics it is possible to represent the materials in numerical simulation models as an equivalent fluid.

Figure 5 illustrates the validation by comparing the characteristic impedance and wave number obtained through the Horoshenkov and Swift model and the two experimental methods for the sample 2 of the mixture 2, grain size 02 and 4 cm. This material showed interesting characteristics, presenting an absorption coefficient curve wide in terms of frequency, even with 4 cm thickness.

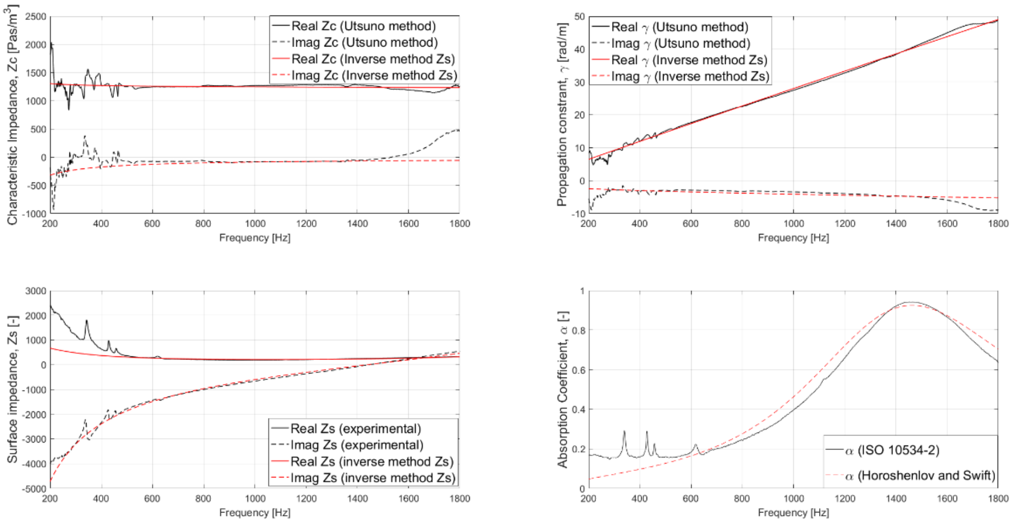

Figure 5. Validation of the comparison between the experimental methods and the Horoshenkov and Swift method based on macroscopic parameters obtained through the inverse method.

Table 2. Macroscopic parameters.

Grain mixture	Grain Size (mm)	Thickness (cm)	Sample	ϕ^* (-)	σ (Pa s m^{-2})	α_∞ (-)	σ_p (ϕ-units)
Mixture 1	2-4	4	1	0.39	5975.01	1.90	0.23
			2	0.38	5116.68	2.22	0.29
		6	1	0.37	3002.08	1.98	0.10
			2	0.35	5108.15	2.17	0.17
	3-8F	4	1	0.38	5531.43	1.91	0.27
			2	0.35	6284.03	1.67	0.48
		6	1	0.40	2743.12	1.76	0.21
			2	0.38	4879.71	1.77	0.31
Mixture 2	0-2	4	1	0.48	4746.09	1.91	0.16
			2	0.47	4616.48	1.81	0.28
		6	1	0.47	5153.07	1.74	0.24
			2	0.45	3980.64	2.08	0.23
	2-4	4	1	0.37	4040.76	2.64	0.14
			2	0.35	4133.58	2.41	0.26
		6	1	0.31	5697.06	2.72	0.27
			2	0.31	8283.13	2.81	0.41
	3-8F	4	1	0.31	7037.52	2.05	0.32
			2	0.35	4872.08	2.00	0.33
		6	1	0.31	8121.22	2.40	0.21
			2	0.35	3369.52	1.91	0.29
Mixture 3	0-2	4	1	0.41	5898.03	2.63	0.22
			2	0.34	10556.50	2.99	0.22
		6	1	0.32	8629.80	2.99	0.37
			2	0.33	5673.70	2.94	0.40

5. CONCLUSIONS

In this work, the acoustic properties of consolidated granular materials for use in noise control strategies are presented and theoretically and experimentally analysed. For this purpose, several samples with different grain sizes, mixtures and thickness were produced in the laboratory. Experimental techniques making use of an impedance tube were adopted to obtain the absorption coefficient, surface impedance, characteristic impedance and wave number of each sample. Through a combination of experimental measurements and an inverse method, the four macroscopic parameters used in the Horoshenkov and Swift model to represent and predict the behavior of the sound absorption were obtained.

Through the experimental characterization in impedance tube of each sample, it was observed that, when two samples of the same grain size and mixture but different thickness, the sample with greater thickness shows a displacement in the curve of absorption coefficient towards lower frequencies. When comparing samples with the same thickness and grain size, but different mixtures, the samples with greater quantity of cement show higher absorption at lower frequencies, being more significant in the samples with smaller thickness. The influence of the grain size shows that the smaller grain size tested presents a wider absorbent behavior in terms of frequency than the other grain sizes.

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