



EPS foam blast attenuation in full-scale field test of reinforced concrete slabs

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ABSTRACT. Predicting explosion parameters is an important step when planning for blast tests or the design of blast resistant buildings. This paper presents a comparison of recorded pressure that was reflected on the surface of reinforced concrete slabs with and without EPS (Expanded Polystyrene) foam retrofit measured from a detonation of 2.7 kg of non-confined plastic explosive. Two 50 MPa reinforced concrete slabs measuring 1.0x1.0x0.08 m, simply supported on two sides were tested. The explosive was suspended at a distance of 2.0 m from the upper surface of the slabs; one of the slabs had 5.0 cm thick foam on the top side. Eight piezoelectric pressure sensors were positioned at a distance of 2.0 m from the explosive. Results showed that the foam retrofit reduced the reflected pressure by approximately 57% when compared to the slab without EPS foam retrofit.

Keywords: blast test; expanded polystyrene; non-confined plastic explosive; pressure reduction; reflected pressure.

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Introduction

Chemical explosions can cause damages and injuries far from their sources, depending on the charge of the explosive and the surrounding medium where the explosion occurs. Explosive effects on structures and people have been studied for decades resulting in improved mitigation strategies for minimizing damages and injuries caused by accidental or intentional explosions (Karagiozova et al., 2009). Most buildings that are subjected to blast effects have structural elements made from reinforced concrete and can fail during the explosion. This event can generate progressive collapse increasing the number of victims and damages on the structure. Reinforced concrete behavior in events of explosions has been studied over the last few years with different reinforcement ratio and compressive strength (Mendonça, Urgessa, Iha, Rocha, & Rocco, 2018). Novel retrofitting technologies have been developed in order to protect structural elements and avoid huge damages and loss of lives. According to Bartholomew, Marsh, and Hooper (1992) part of the energy coming from an explosion is reflected, part is transmitted and part is absorbed. Schenker et al. (2008) verified in full-scale field tests that aluminum foam could reduce 50% the acceleration of the slab retrofitted with the foam. The blast wave created by detonation of a high explosive moves forward and expands in a spherical shape, but at a farther distance, the front wave becomes plain (Rao, Kumar, Rao, & Prasad, 2015). Simulations made by Wu and Sheikh (2013) verified the attenuation of blast wave using aluminum foam retrofitting on reinforced concrete panels and comparing results to full-scale tests. Additional research on the use of aluminum foam to protect structural elements, was reported by Shim, Shin, and Yun (2013) using simulations of blast effects on aluminum foam panels. The reduction of blast effects was reported to be approximately equal to 50% in these simulations. Thus, researches with reinforced concrete panels or slabs have been widely used to study these effects. The parameters associated with explosive effects, such as pressure, impulse, and time of duration are important to evaluate the magnitude of the damage caused by explosives. This paper compares the recorded pressure values of an explosion during the interaction with two 50 MPa reinforced concrete slab measuring 1.0x1.0x0.08 m, with and without 5.0 cm thickness EPS (Expanded Polystyrene) foam retrofit. The slabs were supported on two sides, and the explosive was in 2.0 meters stand-off distance above the slab. Both tests had the same scaled distance (Z), defined by Equation 1,

where R is the standoff distance in ‘meters’ and W is the equivalent TNT (TriNitro Toluene) mass in kilograms (Rigby, Tyas, & Bennett, 2014; Castedo et al., 2015).

$$Z = \frac{R}{W^{\frac{1}{3}}} \quad (1)$$

This research shed light on procedures of designs to protect structural elements and assets against blast event providing the reduction of reflected pressure in the surrounding medium of the explosion.

Depending on the ignition-sensitivity, the explosives are classified as primary or secondary. Primary explosives are less stable than secondary, requiring lower energy to ignite; although secondary ones require higher energy in the ignition process, they can cause more damage and are called high explosives (Akhavan, 2004). Shock waves developed by the explosion of primary explosive are employed for igniting a secondary explosive; this sequence is called explosive train.

The aim of this work is the analysis of EPS foam capacity to reduce peak pressure coming from an explosion of non-confined plastic explosive in a full-scale test.

Material and methods

Two 50 MPa reinforced concrete slabs supported on two sides, having the same reinforcement ratio, were tested for explosive effects at Science and Technology Aerospace Department (DCTA) in Brazil. The detonation of 2.7 kg equivalent TNT non-confined PBX (Plastic Bonded Explosive) explosive above the slab generated shock waves that hit the upper surface of the it. The explosive shape was cylindrical, measuring 20 cm in height and 10.5 cm in width. The explosive train was assembled with the primary explosive in a cavity on the top of the main charge (secondary explosive), see Figure 1. The explosive was triggered by an electric fuse attached by wires from a bunker at a distance of 250 m, where the research team was housed during the detonation. It is an unprecedented test accomplished in Brazil using PBX against reinforced concrete slabs simply supported on two sides, with and without EPS foam retrofit.

The pressure sensors used in the tests have a sensitivity of up to 5.0 MPa and a sampling time of 10 μ s. Figure 2 shows the explosive positioned above the slab before one of the tests, the slab has 5.0 cm EPS foam on top and pressure sensors are in the right position. Sensors close to the slab were able to record reflected pressure and sensors pointing to the explosive were able to measure incident peak pressure. Scaled distance for both tests were 1.43 m $\text{kg}^{-1/3}$ with the same stand-off distance (2.0 m). The measured pressure can be compared to the result of Equation 2, used for prediction of reflected pressure (Kinney & Graham, 1985), however, depending on the surrounding elements, the reflected pressure may have values from two to eight times the incident pressure (American Society of Civil Engineers [ASCE], 2010; Hua, Akula, & Gu, 2014; Trajkovski, Kunc, Perenda, & Prebil, 2014).



Figure 1. Primary explosive on top of the main charge.

$$P_r = 2P_{so} \left[\frac{7P_o + 4P_{so}}{7P_o + P_{so}} \right] \quad (2)$$

P_r represents reflected pressure, P_{so} denotes the incident pressure and P_o is the atmospheric pressure. Incident pressure is given by the widely used Equation 3 (Kinney & Graham, 1985).

$$P_{so} = P_o \frac{808 \left[1 + \left(\frac{Z}{4,5} \right)^2 \right]}{\sqrt{\left[1 + \left(\frac{Z}{0,048} \right)^2 \right]} \times \sqrt{\left[1 + \left(\frac{Z}{0,32} \right)^2 \right]} \times \sqrt{\left[1 + \left(\frac{Z}{1,35} \right)^2 \right]}} \quad (3)$$

The main reason for using a non-confined explosive is due to the non-generation of explosive fragments. This guarantees that the pressure measurements are less likely to be affected by fragments, even if the standoff distances are small.

Dimensions of the slabs were 1.0x1.0 m in plain and 0.08 m in thickness. Concrete compressive strength was 50 MPa for both slabs; it was a sample of the support wall reinforcement on the bridge of Presidente Dutra Street at km 28 in Cruzeiro City, State São Paulo. Reinforcement ratio in one direction was 0.175 (7 rebar of 5 mm) and 0.37% (7 rebar of 5 mm and 2 rebar of 10 mm in the center) in the perpendicular direction. Concrete cover was 2.0 cm according to Brazilian Normalization Board (NBR 6118; *Associação Brasileira de Normas Técnicas* [ABNT], 2014) and the reinforcement was placed in the bottom face of the slabs to carry positive moment. One of the slabs had 5.0 cm thick EPS foam stuck on the upper surface, see Figure 3; it is a lightweight material, not expensive and widely used in constructions (Orçati, 2016). This procedure was applied to verify if the foam could mitigate recorded reflected pressure. EPS foam was chosen because of the presence of gas inside the foam, which works similarly to a spring attenuating the displacement of the shock front wave.

Explosions near the structures develop reflected pressure (Li, Wu, Hao, Wang, & Su, 2016). Foam has a long plastic plateau and can absorb part of the energy and reduce values recorded by the sensors (Wu & Sheikh, 2013). EPS foam was characterized using FT-IR verification at *Laboratório Instrumental da Divisão de Química do Instituto de Aeronáutica e Espaço* (IAE), located at *Departamento de Ciência e Tecnologia Aeroespacial* (DCTA) in Brazil. Infrared spectrometer used for the analysis was SPECTRUM ONE PerkinElmer®, under conditions: mid-infrared (4000-400 cm^{-1}), resolution of 4 cm^{-1} , gain from 1 to 20 scans for qualitative analysis. Transmission mode was used for obtaining EPS spectrum. The sample was prepared as casting film by using hot toluene.

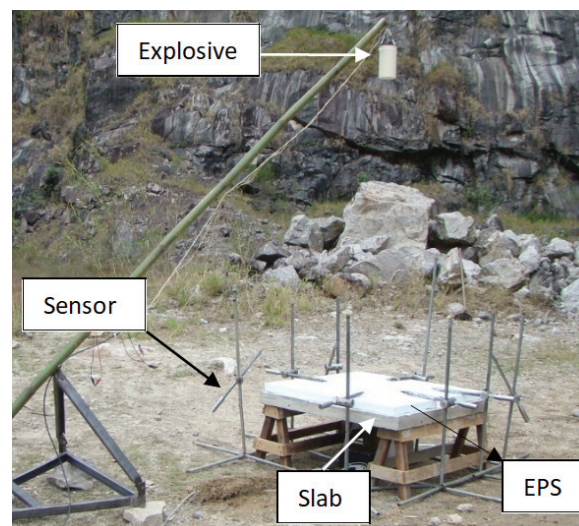


Figure 2. Set up for the test.

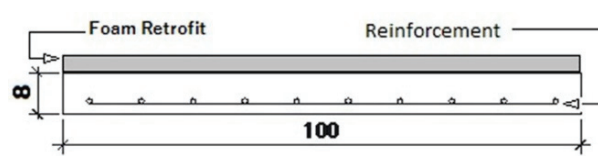


Figure 3. Slab cross-section with foam retrofit (dimensions in cm).

Results and discussion

EPS foam shows infrared characteristics band, assigned to aromatic groups between 3100 and 3000 cm^{-1} (ν C-H group, weak to medium intensity), 1600 and 1500 cm^{-1} (ν C=C, medium or variable intensity) and strong bands between 900 and 600 cm^{-1} (δ C-H- substitution position) (Smith, 1979; Silverstein, Bassler, & Morrill, 1981; Hummel & Scholl, 1984).

The similarity between polystyrene (PS) characteristic bands and EPS foam spectrum is observed when its spectra are compared (Figure 4). The presence of gas inside EPS is the reason for using it, instead of PS.

Four pressure sensors were able to record peaks of reflected pressure in both tests. First test (slab 1) without EPS foam retrofit recorded average values of reflected pressure higher than the second one (slab 2), where EPS foam was placed on top of the slab. Table 1 shows the peak of reflected pressure recorded, average and sample standard deviation (SSD) values.

Sample standard deviation showed that sensors on slab with EPS foam recorded more consistent values due to its small value of SSD. Slab with no foam provided less consistent values due to the multiple reflections on the surface without foam.

Predicted incident pressure given by Equation 3 was 450 kPa . Results of reflected pressure are in agreement with the range mentioned in the literature, from two to eight times the incident pressure (ASCE, 2010; Hua et al., 2014; Trajkovski et al., 2014). In addition, according to research of Kelliher and Sutton-Swaby (2012), for scaled distance of $1.43\text{ m kg}^{-1/3}$ reflected pressure can reach values close to 4000 kPa , depending on the surrounding area of the test.

Using Equation 2, the predicted reflected pressure for slab 1 was 1950 kPa , and for slab 2 was 1960 kPa . These calculations do not take into account the variation caused by EPS foam. Both values are 20% lower than average of recorded value of slab 1, without EPS foam. It is worth to note that the average of reflected pressure for slab with foam (slab 2) was 46% lower than the predicted reflected pressure. Comparing only recorded values, the reduction of reflected pressure by use of EPS foam on top of the slab 2 reached 57%. Figure 5 shows the comparison of slab without foam retrofit and slab with foam retrofit.

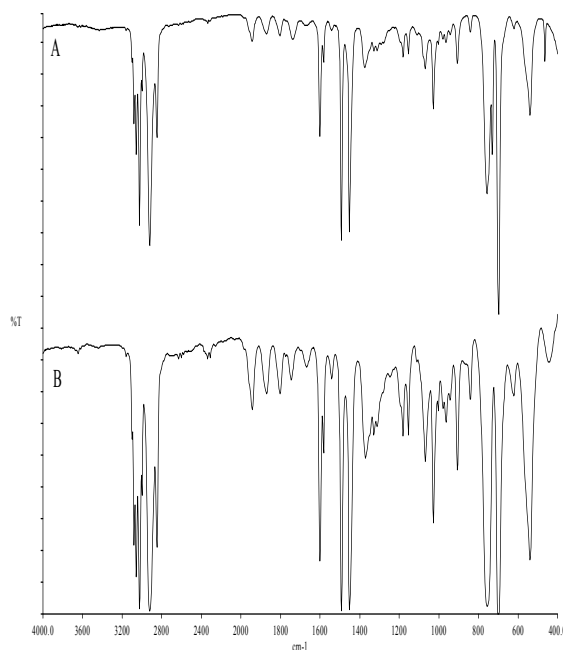


Figure 4. (A) Transmission FT-IR spectrum of EPS foam sample (casting film by toluene). (B) Transmission FT-IR PS reference spectrum (Hummel&Scholl, 1984).

Table 1. Reflected pressure recorded

Sensors	Slab 1 (kPa)	Slab 2 (kPa)
1	2634	998
2	3801	1026
3	2159	1219
4	1327	961
Average	2480	1051
SSD	1032	115

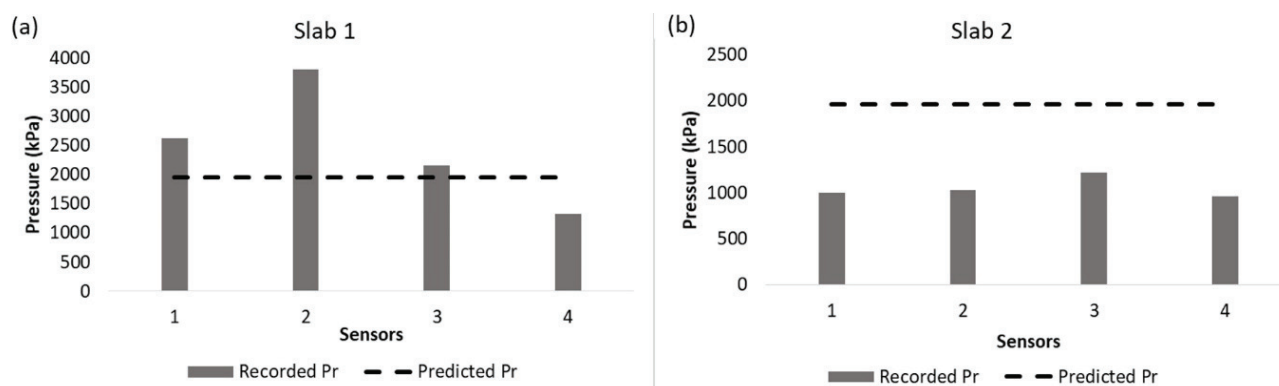


Figure 5. Recorded and predicted pressures for slabs without (a) and with foam (b).

Slab 1, without foam retrofit, recorded three values higher than the predicted reflected pressure. Only sensor 4 recorded a value 31% lower than the predicted one. This effect may have happened because the slab works as a finite target, therefore clearing effects can reduce the recorded value. As sensor 4 was close to the support of the explosive, the clearing effects may have caused the reduction observed on the recorded value. For slab 2, all the sensors recorded pressures lower than the predicted reflected pressure. In this case, the capacity of the EPS foam to halve the reflected pressure in the environment of the explosion has called some attention. Due to the EPS gas content, the recorded pressure was significantly attenuated, according to the gas high compressibility. Even though attenuation of EPS foam was shown, it is worth to note that foam behavior faced to fire can generate contamination of the air, which needs to be considered in planning to use this material for indoor retrofit.

Conclusion

Two slabs with 50 MPa reinforced concrete with the same reinforcement were tested in a full-scale blast test with 2.7 kg of non-confined plastic explosive. The slabs were simply supported on two sides and had 1.0 m² and thickness of 0.08 m. The scale distance was 1.43 m kg^{-1/3} and one of the slabs had 5.0 cm EPS foam retrofit in order to verify the capacity of the foam to reduce the recorded reflected pressure. The characterization of EPS foam using FT-IR method confirmed that this foam was polystyrene and could classify this material with the capacity to reduce reflected pressure when shocked by blast wave. The records showed that EPS foam provided an average 57% reduction of reflected pressure when compared to the slab without foam retrofit. There was a reduction of 46% when compared to the theoretical predicted pressure. These results showed that EPS foam could mitigate reflected pressure in an explosion environment. Both predicted and recorded reflected pressure are in agreement with the range of reflected pressure found in the literature.

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