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Study on Blast Pressure Resistance of Foamed Concrete Material

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Abstract

Great demand exist for more efficient design to protect personals and critical components against explosion or blast wave, generated both accidentally and deliberately, in various blast scenarios in both civilian and military activities. Concrete is a common material used in protective design of structures. Recently, the demands on producing the lighter concrete material have become interest in concrete research. Foamed concrete is a possible alternative of lightweight concrete for producing intermediate strength capabilities with excellent thermal insulation, freeze-thaw resistance, high-impact resistance and good shock absorption. This paper explores the role and development of Blast Pressure Resistant Materials (BPRM's) on foamed concrete. The explosive tests were conducted to determine the blast mitigating properties. The results show that when the foamed concrete density is increases the blast energy absorption capability will be decreases due to reduce of cavity volume. This is suggested that cavity plays an important role to dissipate and absorb the shock energy of the blast.

Keywords: load, cellular material, foamed concrete

1. INTRODUCTION

An escalation of worldwide terrorism has both demonstrated and highlighted the poor response of conventional structures to both resist local and progressive collapse and to protect personnel. This then also highlights the risk of accidental explosions. There have been many events to highlight the above over the last twenty years in particular. The Oklahoma Bomb in 1995 is a clear example of how progressive collapse of a structure after an explosive event may contribute to the vast majority of the death toll. The building itself was designed for a wind loading of 1.2KPa, however, forensic engineering determined that the peak over-pressure created by a hemispherical explosive at a stand-off distance of 10m was estimated to be in the range of 13.6MPa. As a result of the detonation, a total of 168 people lost their lives and many more were injured [1]. A staggering 90% of the people who lost their lives did so indirectly as a result of structural progressive collapse.

Due to growing concern, engineers continue to identify and develop candidate materials to help enhance the ability of a conventional structure to resist and protect personnel against the effects of blast waves. For a BPRM to be effective it should have a particular set of properties, it should have a sufficient compressive strength, ductility, fracture toughness, resistance to corrosion and ultimately, be manageable as blast mitigation schemes often take the form of a structural retrofit [1]. However, this has to be balanced with other considerations such as, a priority of cost, weight, volume, building cosmetics, fit and function [1].

Blast loads on structures are traditionally divided into confined and unconfined explosions. These categories are then again sub-divided into a further three sub-categories dependent upon the blast loading caused within the actual structure [2]. Explosions occurring within a structure produce very high incident and reflected over pressures. The structure as a system will also suffer increased residual static pressures resulting from the degree of heat and product containment. As a result of this, a structure may be damaged further due to sustained exposure to fire. Categories may be described as follows. A confined, fully vented explosion describes an event where the explosion takes place within or within a minimal stand off distance from a structure. Therefore, the incident over-pressure is amplified by any surface that may survive the event and the explosive product is vented to the surrounding atmosphere [2]. A partially confined explosion describes an event taking place within a structure were shock pressures are forced to reflect from surfaces and there is a limited ability for the explosive product to escape giving rise to an increase of static pressure within the system [2]. A fully confined explosion describes full containment and immediate incident over-pressure reflection with a sustained, small amount of product leakage and a very large increase in static pressure within the system [2]. Unconfined explosion are classed and described as follows. A free air burst explosion is characterized by a free air explosion were incident over-pressure are not immediately reflected

[2]. An air burst explosion occurs at a stand-off distance and at an altitude greater than zero but less than the stand-off distance so that incident over pressure is amplified at the ground prior to a structure [2]. It should be noted that large altitudes the static pressure of air will lesson the effects of blast [3]. For an explosion to be classed at a surface burst it incident over-pressure must be immediately reflected from the ground prior to meeting a structure [4].

The extent of exposure undergone by such a structure is a quantitative function of the particular explosive used and is therefore judged by the following factors: explosive material, output energy order, charge weight, Stand-off distance the geometry of the surrounding area or surface interaction of pressure incident over-pressures [2-5]. It is generally, an understanding of the above that enables one to predict blast pressure development.

Generally, the main aim of explosively testing materials is to determine their ability to dissipate and absorb blast wave energy. Some tests may be universal but the type of testing conducting is usually determined by the context in which the material may be used.

To this end, various experiments have been conducted on possible BPRM's. Cooper and Kurowski during the 1970's detonated charges within varying densities of blocks of Rigid Polyurethane Foam so that they could consider the materials response by the cavities generated [5]. During the 1990's, Ronald L. Woodfin extended this work by detonating charges that were in bedded and on the free surface. From reduction of data from other similar experiments, Woodfin concludes that RPF's exhibit a remarkable of a capability to absorb and dissipate energy of a blast wave [5-6]. A number of material properties are then suggested for this attribute, these include, compression of the gas in the cells, multiple "micro-reflections" from the many cells encountered by the blast wave, chemical reactions induced in the gas and in the polyurethane, radiant heat transfer, strain energy in the polyurethane, secondary burning of the affected material, and acceleration of the affected materials [5].

This paper explores the role and development of Blast Pressure Resistant Materials (BPRM's) on foamed concrete. The explosive tests were conducted to determine the blast mitigating properties.

2. MATERIAL PROPERTIES

The foamed concrete is made of a combination of fine sand, cement, water and special foam provided by E-A-B Associates. It contains large amount of air bubbles. The density of plain foamed concrete is determined by the amount of the foam added to the basic cement, sand and water mixture. Generally, the range of its dry densities can be made from 400 kg/m3 to 1600 kg/m^3 and the corresponding range of compressive strengths is from 1 to 15 MPa [E-A-B Associates technical note]. In this study, the ranges of dry densities were chosen between 700 kg/m^3 and 1200 kg/m^3 and about two batches of foamed concrete have been produced. The guideline table of the mixing ratio for 1m^3 plain foamed concrete is shows in Table 1.

Table 1: Design mix of foamed concrete [E-A-B Associates technical note]

No.	Subject	Quantity	
		Mix 1	Mix 2
1	Dry density (kg/m3)	799	968
2	Wet density (kg/m3)	940	1140
3	Sand: cement: water	1:1:0.6	1:1:0.6
4	Cement(kg)	352	431
5	Dry sand(kg)	352	431
6	Water(kg)	211	258
7	Slurry Density (kg/m3)	2005	2005
8	Foaming Agent(1 liter)	0.74	0.60
9	Water(1 liter)	25	20
10	Foam(1 liter)	543	441

The indentation tests were performed to investigate the properties of foamed concrete. It is noted that the foamed concrete specimens need to be cured for 28 days before the test is performed.

In the Rigid, Perfectly-Plastic, Locking model, (R-P-P-L) [8], the locking strain and the equivalent plateau stress are two important parameters to be determined. The densification strain is used to obtain the locking strain in R-P-P-L model. The densification strain is determined by the maximum energy absorption efficiency [9-10], i.e.

$$\left.\frac{d\eta(\varepsilon)}{d\varepsilon}\right|_{\varepsilon=\varepsilon d} = 0 \qquad (1)$$

where the energy absorption efficiency is given by

$$\eta(\varepsilon) = \frac{1}{\sigma\ (\varepsilon)}\int_0^{\varepsilon} \sigma(\varepsilon) \qquad (2)$$

based on the indentation stress-strain curve of the foamed concrete.

The equivalent plateau stress is determined by equating the energy absorbed in R-P-P-L model to the deformation energy in actual stress-strain curve up to locking strain [9-10], i.e.,

$$\sigma_p = \frac{\int_{\varepsilon_{dr}}^{\varepsilon_D} \sigma\ (\varepsilon) d\varepsilon}{\varepsilon_D - \varepsilon_{cr}} \qquad (3)$$

where ε_{cr} is the strain at yield corresponding to the start of the plateau regime.

An example for the determination of the densification strain using the energy absorption efficiency-strain curves is shown in Figure 1 and the material property data obtained from indentation tests are given in Table 2.

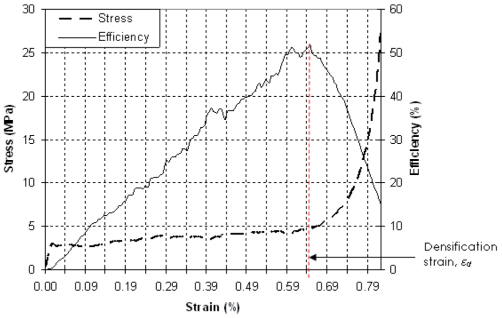


Fig. 1 Determination of densification strain using the energy absorption efficiency-strain curves (1INT1)

Table 2: Properties of foamed concrete

Test	Batch	Average batch density (kg/m^3)	Specimen	Locking strain ε_l	Plateau stress σ_p (MPa)
1	1	915.0	1INT1	0.65	4.4
2			1INT2	0.68	4.7
3	2	1109.7	2INT1	0.74	6.7
4			2INT2	0.74	6.3

3. EXPLOSIVE TEST

Firstly, before testing all of the samples were marked on each surface so that fragments original position could be identified. Samples were then drilled so that a RP80 detonator could be placed into the geometric centre as shown in Figure 2. It should be noted that for safety reasons, the detonators were only placed within the sample when it was ready to be tested. To again make the process of reconstruction simpler, after drilling the samples they were wrapped loosely in paper and tape. It was hoped that this would constrain the fragments displacement and perhaps maintain some of the geometry after fragment generation. Once ready, the sample would be placed within the explosive chamber as shown in Figure 3 at which point the detonator could be wired up to the trigger device. Once the alarm to alert people of a detonation taking place had been sounded the trigger was powered to 40KV and the RP80 detonated. The results of the detonation were then finally collected for later analysis.

Fig. 2 Detonator charge insertion

Fig. 3 Explosive chamber

4. RESULTS AND DISCUSSION

Five samples of each mix design were explosively tested. The type of test conducted is a preliminary type of experiment when investigating a materials possible application as a BPRM [5] enabling one to examine cavity, fragment generation, crushing and deformation patterns. It is this phenomenon that gives indication of a materials ability to dissipate and absorb blast energy.

There was a notable difference between the response of the two foamed concrete mix designs despite a relatively small difference in density and compressive strength of approximately, 195kg/m3 and 2MPa. In all of the samples, clearly identifiable cavities were generated as a result of the detonation process (as shown in Appendix A). These cavities were formed milliseconds after detonation due to very high pressure and heat, by which the size of the cavity is determined by the point at which equilibrium is reach between the destruction of the material due to high pressure, heat and the compressive strength of the foamed concrete. In the vertical direction, the cavities generated were found to make an average of 49 and 37mm, in the horizontal direction the averages made 40.8 and 33mm respectively for design mix one and two (as shown in Table 3-4). The difference between the horizontal and vertical dimensions is attributes to blast energy escaping upward of the cavity through the shaft through which the detonator was placed. The difference of 12 and 7.8mm indicates simply that the RP80 detonator was able to generate a larger cavity within mix design two as a direct result of differing densities and therefore, compressive strength of the medium.

For mix design one and two and out of the five samples tested for each, an average fragment number was recorded to be 5.2 and 6.4 respectively (as shown in Table 3-4). This result may be explained by there being a slightly less degree of ductility within mix design two as there is more aggregate material and therefore, affecting its performance when exposed to a very short, high frequency event. It may also go a small way to suggesting that there may be an inversely proportional relationship between cavity size and fragment size when one varies foamed concrete density. Hence, increasing density/compressive strength decreases cavity volume and increases fragment generation. As a result of this and within the context of a close in detonation, one may want to consider a least dense foamed concrete allowable and thereby reduce dead weight local to a conventional structure.

Table 3: Foamed Concrete Design Mix 1 Post Explosive Observations

Design Mix: 1				
Sample	Crater Height (mm)	Crater Width (mm)	Fragment Number	Comments
1	50	60	9	
2	50	50	3	
3	50	40	5	
4	50	45	4	
5	45	50	5	
Average	49	40.8	5.2	

Table 4: Foamed Concrete Design Mix 2: Post Explosive Observations

Design Mix: 2				
Sample	Crater Height (mm)	Crater Width (mm)	Fragment Number	Comments
1	40	35	3	3 Column Fractures
2	45	35	4	
3	30	25	14	Crater Formation
4	35	40	5	
5	35	30	6	
Average	37	33	6.4	

This observation suggests that if one is to increase the volume of solid material within the foamed concrete the material is less able to dissipate and absorb the shock energy of the blast from the RP80 detonator. However, this may be explained by theory of cellular materials under blast loading – with less solid material and more air in the sample, the are more open celled spherical structures (one of the most efficient force distributing structures under compression). Hence, design mix one is better able to absorb and dissipated the shock waves driven into the material.

There were no signs of shock energy being dissipated through deformation or crushing of the foamed concrete outward of the cavities themselves. However, this result was expected due to a lack of ductility owing to the aggregate material (sand) used to make foamed concrete. Therefore, it may be concluded that the overall blast wave response of the foamed concrete was by cavity generation and fracturing. The above observation would suggest that foamed concrete could only be used as part of a composite system when locally protecting what may be very sensitive systems as blast energy may be transferred to other surfaces through brittle fracture. Again there is also the concern of spall as in conventional concrete.

Within both mix designs it is certain that the cellular structure of the foamed concrete played a considerable role in both the cavity and fragment generation. The speed of sound within the foamed material will be affected by the open celled air pockets and act to attenuate the shock [7]. Without a means to quantify this affect it is not wise to make any other conclusions on its impact aside from research.

There was one irregular result after testing arising from sample three of design mix two. By irregular, one means there was a degree of radial spalling outward of the drill shaft on and through the free surface. This spalling is a result of reflected tensile stress waves from the free surface overcoming the tensile strength of the foamed concrete [6]. As this was the only sample were spalling was present it is suggested that the detonator may not have been correctly placed within the sample (at the geometric centre). As a result, the reflected tensile stress waves may have been greater in magnitude nearer the top free surface resulting in spalling.

5. CONCLUSIONS

The explosive test had been conducted in order to study the Blast Pressure Resistance Material (BPRM) on foamed concrete. It is noted that when the foamed concrete density increases the blast energy absorption capability will decrease due to reduce of cavity volume. Thus, it is suggested that cavity plays an important role to dissipate and absorb the shock energy of the blast.

REFERENCES

[1] R. Lane, B. Craig, W. Babcock. *Materials for Blast and Penetration Resistance*. AMPTIAC Quarterly, Rome (2001).

[2] TM5-1300, *Design of Structures to Resist the Effects of Accidental Explosions*. US Dept. of the Army Technical Manual (1991).

[3] Baker W. E., Explosions in Air. University of Texas Press, Austin, Texas (1973).

[4] P. D. Smith, J. G. Hetherington, *Blast and Ballistic Loading of Structures*. Butterworth-Heinemann Ltd, Oxford (1994).

[5] Ronald L. Woodfin, *Using Rigid Polyurethane Foams for Explosive Blast Energy Absorption in Applications such as Anti terrorist Defences*. Sandia National Laboratories, California (2000).

[6] Bangesh, M. Y. H., Impact an*d Explosion* – Analysis and Design. Blackwell Scientific Publication, Oxford (1993).

[7] A. Teodorczyk, J. Lee, *Detonation attenuation by Foams and Wireless Meshes Lining the Walls*. Shock Waves, Springer – Verlag (1995).

[8] A.M.Ahmad Zaidi and Q.M.Li (2009), Investigation on penetration resistance of foamed concrete, *Structures and Buildings*, Vol.162, Issue SB1.

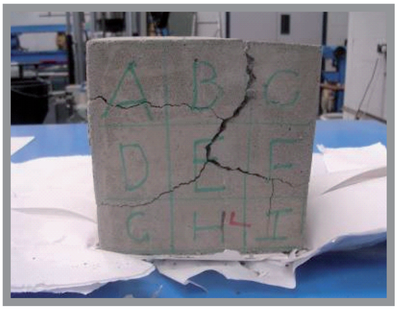
[9] Li, Q.M., Magkiriadis and Harrigan, J.J.(2006). Compressive strain at the onset of densification of cellular solids. *J.Cellular Plastics*, 42, pp. 371-392.

[10]Tan, P.J., Harrigan, J.J. and Reid, S.R. (2002). Inertia effects in uniaxial dynamic compression of a closed cell aluminium alloy foam. *Mater*. Sci. Tech., 18, pp.480–488.

Appendix A: Foamed Concrete Post Explosive Testing

Mix Design 1

Sample L1:



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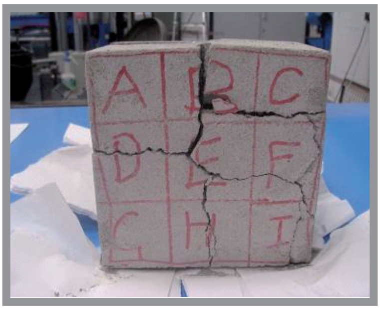

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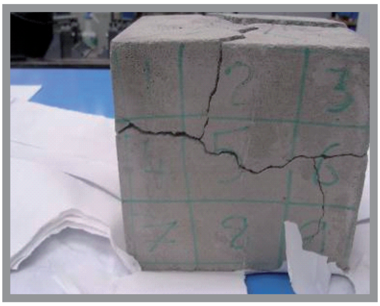

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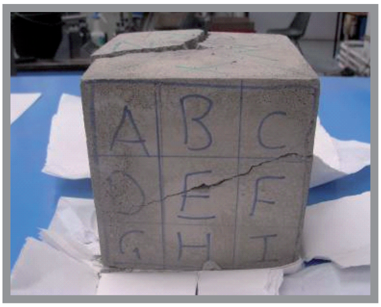

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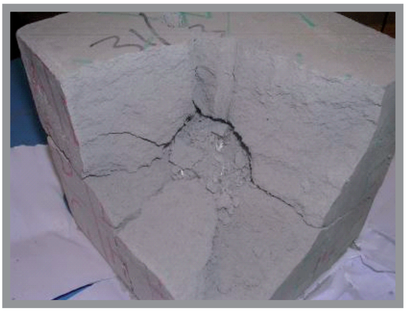

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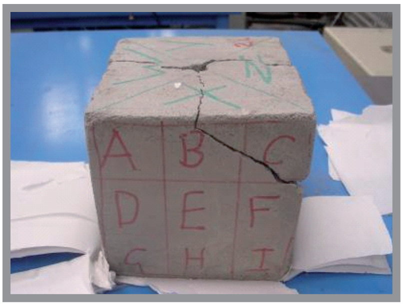

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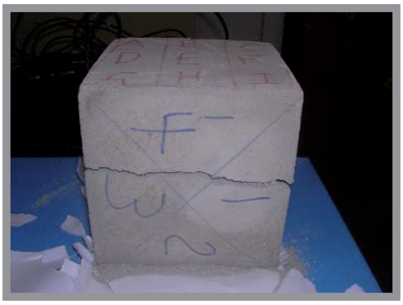

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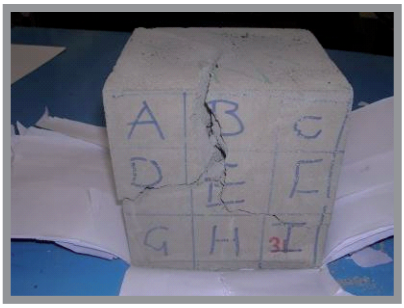

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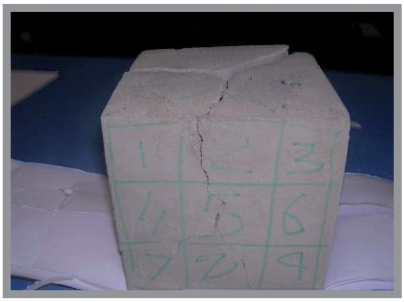

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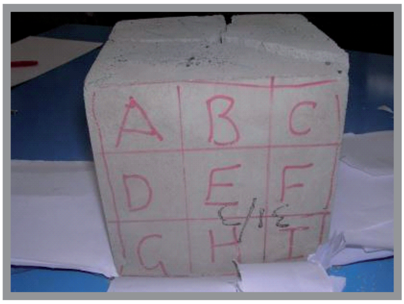

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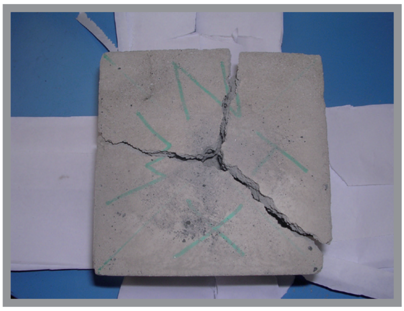

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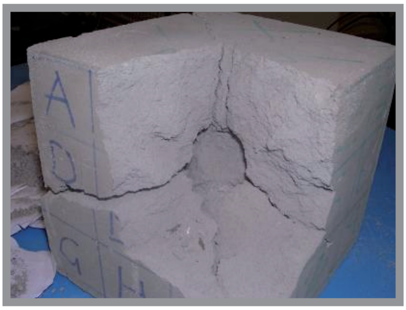

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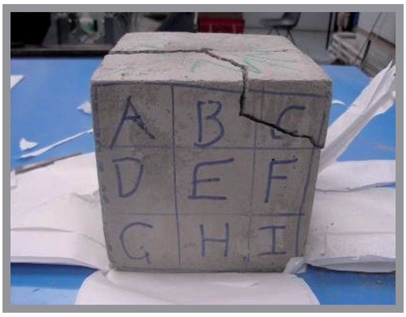

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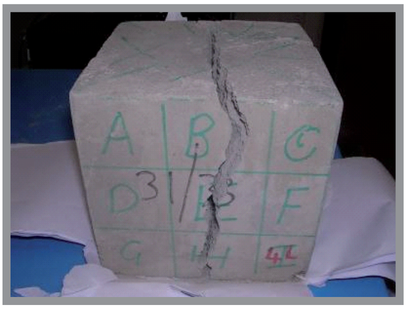

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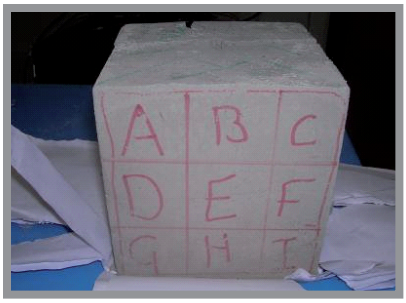

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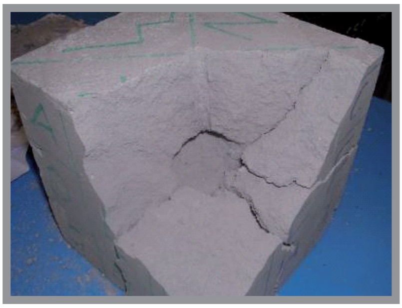

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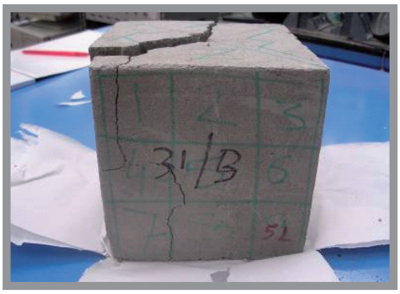

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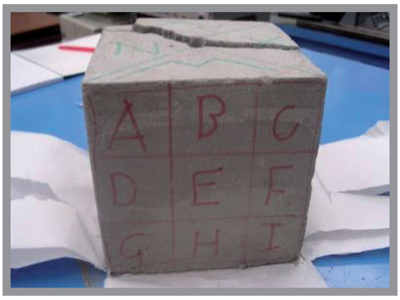

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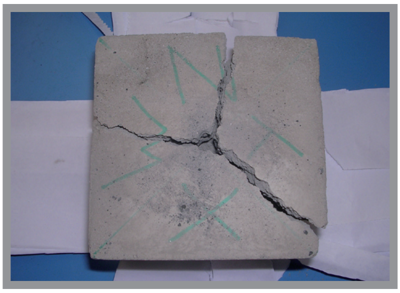

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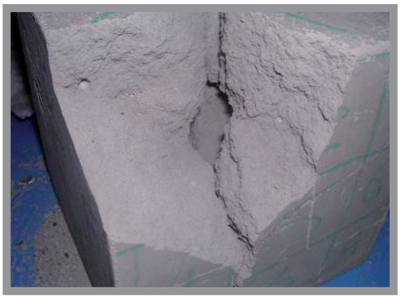

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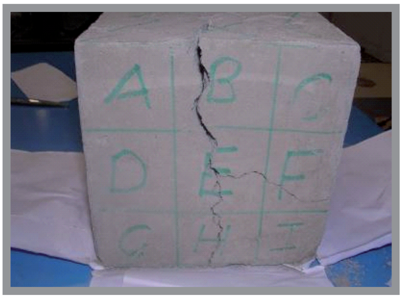

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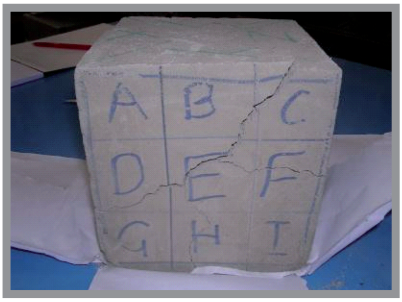

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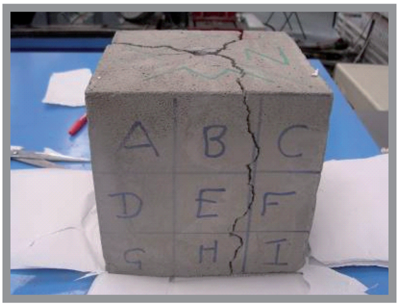

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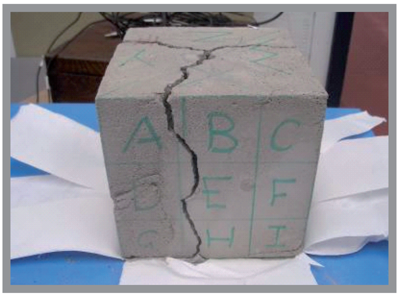

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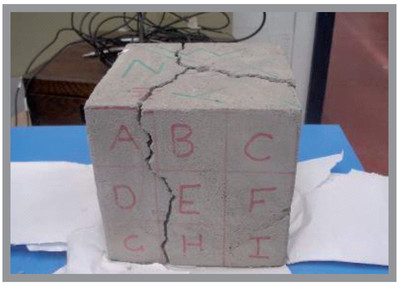

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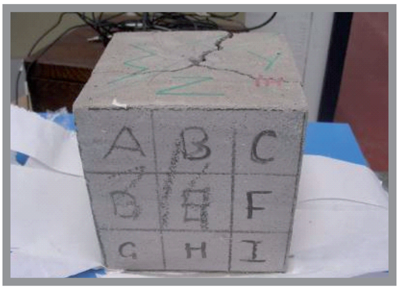

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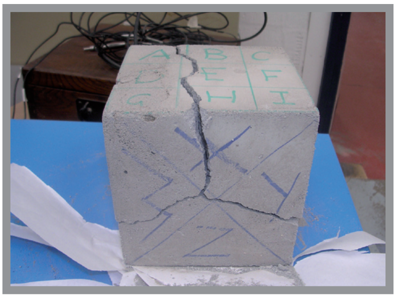

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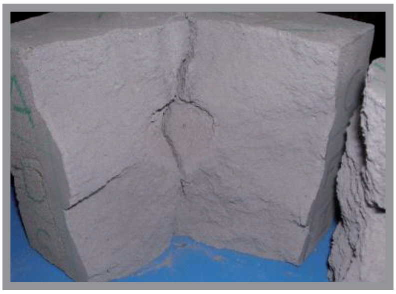

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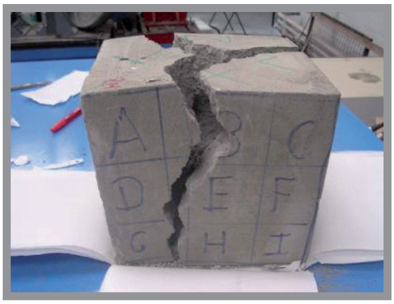

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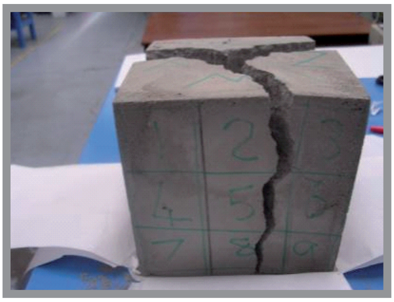

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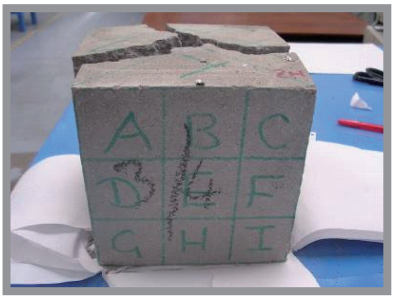

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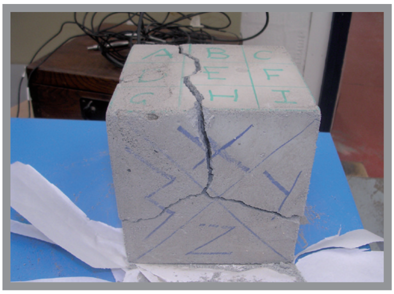

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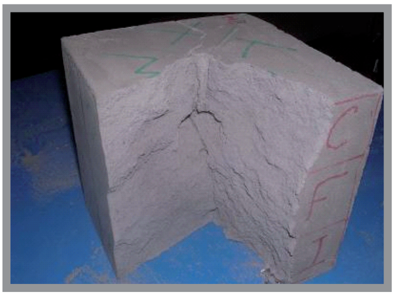


[6]

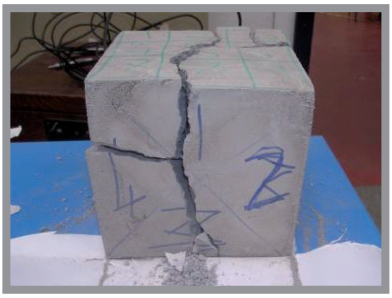
[4]

Sample H3:

[1]

[5]

[2]



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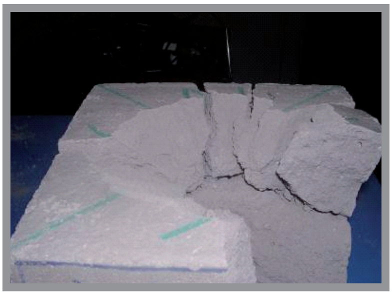

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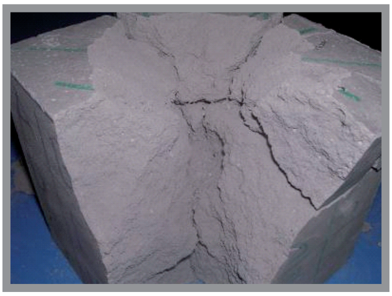
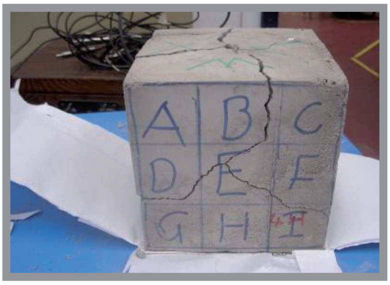


[8]

Sample 4H:

[1]



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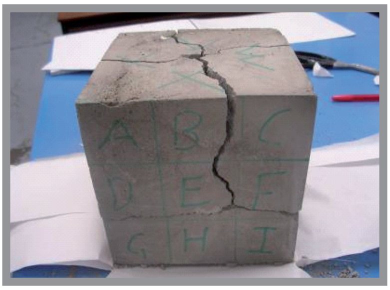
[3]



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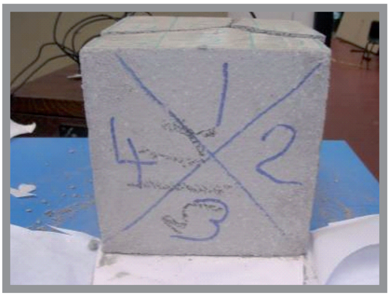

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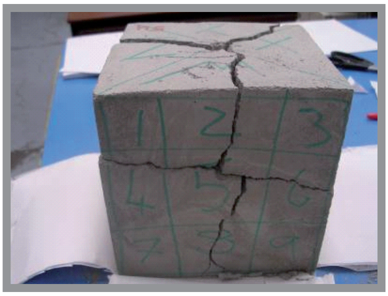
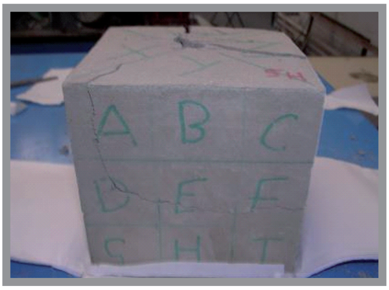


[4]

Sample H5:



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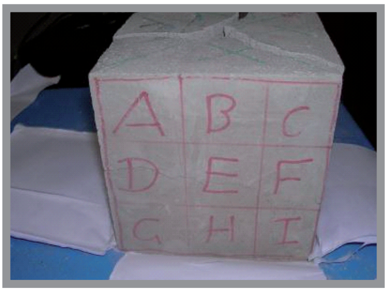

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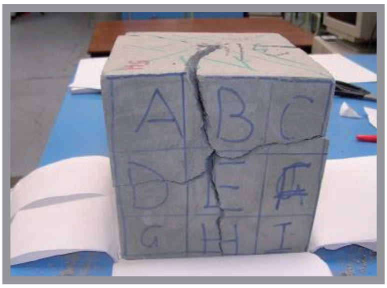

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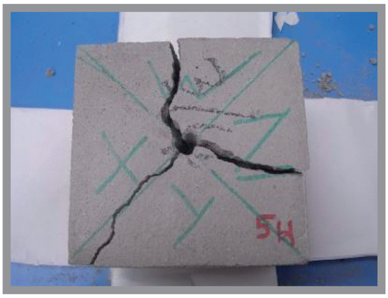

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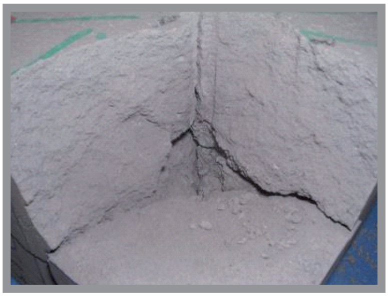
[6]



[7]