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Improved Shock Absorbing Liner for Helmets

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Abstract

This report presents the findings of the project 'Improved Shock Absorbing Liner for Helmets'. A special tool was developed to produce flat samples of foam made of either the new design or the current design. A total of 161 flat foam samples were manufactured and tested to the Australian Standard for motorcycle and bicycle helmets. This included 100 samples with new design and 61 samples with current design. The newly designed shock absorbing foam liner, when compared with the current liner, displayed significantly more crushing, greater time-duration (interaction), less slab-cracking and recorded peak decelerations less than the required 300 g's (g-force).

Keywords

HELMETS, SAFETY, PROTECTION, SHOCK ABSORBING LINERS, IMPACT FORCE, MOTORCYCLISTS, CYCLISTS

EXECUTIVE SUMMARY

This report presents the findings of the Project '***Improved Shock Absorbing Liner for Helmets***'.

Comparative tests were carried out on flat samples of single-density and dual-density foams. The **single-density foam** samples represented typical samples of foam used in liners of current motorcycle and bicycle helmets. The **dual-density foam**, of lower average density and unique configuration, represented the newly designed shock absorbing foam liners.

The objective of the project was to demonstrate that the dual-density foam samples will absorb an impact force more effectively than the current foam liners made of single-density. The new liners are to also abide by the requirements of the Australian/NZ Standards for motorcycle and bicycle helmets. The dual-density foams test-results showed:

- an increase in crushing
- a greater impact time duration
- a decrease in the amount of slab-cracking, and
- the measured peak deceleration (g force) was below the required peak deceleration, as outlined in AS/NZS 2063 (Bicycle) and AS 1698 (Motorcycle).

A total of 161 flat foam samples were manufactured and tested which included 100 samples incorporating the new design and 61 samples with current design.

COMPARISONS OF FOAM SAMPLES - FINDINGS

Findings for Crushing:

- Samples of foam, from Test 1, with dual-densities 70/30 kg/m^3 (A1) clearly showed more crushing than samples with single density 70 kg/m^3 (B1).

- Samples of foam, from Test 2, with dual densities 75/30 kg/m^3 (A2) and samples of foam with same dual density, but reversed (A2R) generally crushed more than samples with single density 75 kg/m^3 (B2).

- Samples of foam, from Test 2, with dual densities 75/30 kg/m^3 (A2) showed roughly similar crushing to samples with same dual densities but reversed (A2R) for drop heights of 1.5m, and cold to ambient temperatures.

- Samples of foam, from Test 3, with dual-densities 75/30 kg/m^3 (A3) and 75/25 kg/m^3 (A4) clearly showed more crushing than samples with single density 75 kg/m^3 (B3).

- Samples of foam, from Test 3, of dual-densities 75/30 kg/m^3 (A3) and 75/25 kg/m^3 (A4) have roughly similar crushing properties for drop heights of 1.5 -1.83 m.

- Hard surfaces of flat steel anvil, bitumen and concrete effect thickness crushing of foam in similar ways, where as road base gives higher and varied results dependant upon its compaction. Higher still are kerb channeling results as crushing occurs on both sides of the foam, i.e. crushing from the Mg-headform and metal kerb.

- Generally, cold (-5^{0}C), ambient (18-25^{0}C) and hot (50^{0}C) samples exhibit similar crushing effects, although hot and wet samples give slightly higher values of crushing. This maybe due to hot expanded air spaces and water giving further absorbent properties to the foam, however these results are inconsistent and inconclusive.

Findings for Impact-Time

- Samples of foam, from Test 1, with dual densities 70/30 kg/m^3 (A1) clearly had a longer time duration than samples with single density 70 kg/m^3 (B1).

- Samples of foam, from Test 2, with dual densities 75/30 kg/m^3 (A2) and samples of foam with same dual densities 75/30kg/m^3 but reversed (A2R) generally had a longer time duration than samples with single density 75 kg/m^3 (B2).

- Samples of foam, from Test 3, with dual densities 75/25 kg/m^3 (A3) and 75/30 kg/m^3 (A4) generally had longer time duration than samples with single density 75 kg/m^3 (B3).

- Samples of foam with dual densities 75/30 kg/m^3 (A2) generally had longer time duration than samples with same dual densities but reversed (A2R).

- Hard surfaces, such as flat steel anvil, bitumen and concrete, have reasonably similar impact-times for the same drop height, whereas road base gives higher results. Even higher results are obtained for kerb channeling impact-times, due to more crushing on both sides of the foam, i.e. crushing from the Mg-headform and metal kerb.

- Generally, cold (-5^{0}C) foam samples result in slightly lower impact-times than ambient temperatures (18-25^{0}C) for the same drop height. Hot (50^{0}C) and wet samples give slightly higher results for a drop height of 1.83m.

- Colder foams generally exhibit more dense-like properties.

- Hot and wet foam samples exhibit more energy absorbing properties for a drop height of 1.83m.

Findings of Impact Energy Attenuation

- All g-forces were within the requirements of the Australian/NZ Standards, i.e. being below 300g's.

- Samples of foam, from Test 1 with dual densities 70/30 kg/m^3 (A1) clearly showed lower peak decelerations than samples with harder single density 70 kg/m^3 (B1).

- Test 2 and 3 gave varied peak decelerations due to post-expanded single-density foam samples.

- Tests of impact on foams, for a drop height of 1.83m, result generally in higher g-forces than do those at lower drop heights.

- The second impact, of the double impact test at 1.83m, always generate higher g-forces than the first impact, indicating an already compressed/crushed and hence a more dense-like foam.

- Hard flat surfaces result in roughly similar g-forces.

- Road base and kerb channeling give lower values of g-forces, and bitumen displays a slight compression under impact.

- Generally, the g-forces decrease slightly over an increase in temperature from -5^{o}C to 50^{o}C.

- Wet foams have similar g-forces to that of dry foams at ambient temperature.

Findings on Cracking

- Samples of foam with single densities (70 kg/m^3, B1, and 75 kg/m^3, B2 and B3) tested to the Australian Standard for motorcycle and bicycle helmets all showed significantly more slab-cracking than samples of foam with dual densities (70/30 kg/m^3, A1, 75/25 kg/m^3, A3, and 75/30 kg/m^3, A2, A2R and A4).

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1.0 INTRODUCTION

1.1 Background to the Study

Helmet use does reduce head and facial injury and fatality in accidental impact-collisions. The aim of motorcycle and bicycle helmets is to reduce the severity of cranial injuries by absorbing impact energy. The absorption of impact energy by the helmet reduces the likelihood of skull fracture and brain contusion. The helmet achieves this by redistributing forces from localized points. (Hurt, Ouellet, and Thom, 1981; M^{c}Swain and Petrucelli, 1984). Helmets must also protect facial, temporal and zygomatic regions of the head (Hurt *et. al.,* 1981).

Of all fatalities recorded, approximately a quarter of Queensland motorcyclists and cyclists, wearing helmets, die from severe head injuries (Figures 1.0 and 1.1). In another third of all fatalities severe head injuries were implicated. For each motorcycle or bicycle fatality in Australia, the cost to the community is close to a million dollars (RACQ 1998). No significant safety improvement for bicycle and motorcycle helmets has been introduced in the last 3 decades.

The aim of this research is to develop a better impact-absorbing liner than is currently being used in the manufacture of bicycle and motorcycle helmets.

A number of researchers have indicated that helmet foam liners are too stiff and hard (Larder, 1984; Gale and Mills, 1984; Corner, Whitney, O'Rourke and Morgan, 1987; Hearn and Sarrailhe, 1978). To maximize protection of the human skull it is necessary that impact forces be absorbed, to the greatest extent possible, within the foam liner. An impact force being absorbed by the liner will be demonstrated by damage to the liner. Research from the University of Birmingham (Larder, 1984) and the Queensland University of Technology (Corner *et. al.,* 1987), on foam liners from fatal accidents, showed little or no evidence of impact damage, indicating a need for a softer absorbing liner. Corner *et. al.,* 1987, reported that the human skull distorted rather than the hard stiff foam liner, resulting in brain damage or death.

The stiffness and hardness of helmet liners are directly related to the stringent performance requirements of the Australian/New Zealand Standard's impact attenuation test (AS1698 and AS/NZS2063). For helmets to be certified to the Australian/NZ Standards, they must satisfy the requirements of two performance tests (a) the energy attenuation test and (b) the penetration test. Both tests require the use of a solid magnesium headform that endeavours to simulate the human cranium. The only resemblance is the shape. The helmet is attached to the headform and dropped from standard heights onto either a flat or hemispherical steel anvil. The penetration test requires a steel conical striker, weighing 3kg, to be dropped from standard heights onto a helmet fitted to a magnesium headform. Only the crown of the helmet is tested. The standard heights, through which the helmets are dropped, are different for motorcycle and bicycle helmets.

It should be noted that the magnesium headform used in testing is more rigid than the human skull and is more capable of producing a crushing effect on the helmet liner. Researchers (Corner *et.al.*, 1987; Mills and Gilchrist, 1991) have demonstrated that this rigid headform should be replaced with one that can more reasonably simulate the human cranium, e.g. the Wayne State University Hodgson Headform. The magnesium headform produces more severe damage to the helmet liner than would be the case for a real head in a similar impact (Corner *et. al.*, 1987). To satisfy the requirements of the Australian/NZ attenuation test (incorporating the magnesium headform) manufacturers and designers have had to provide a relatively stiff polystyrene-foam liner with high densities, from 70 to 90 kg/m^3. Due to the stiffness of the liner, the human head deforms elastically on impact, causing cranium distress. A distortion of 1-2 mm of the skull is the threshold of intracranial damage (Viano, 1985). The bone in the temporal region of the head is more vulnerable as it has only a half to a third of the bone strength of the rest of the skull, and a child's skull is more deformable than an adult's (Corner *et. al.*, 1987). The fracture deformation of a child's skull is between 1.7 and 5 times greater than the adult skull. Bicycle helmets for children are the same as worn by adults, and have the same liners as used for motorcyclists. They also undergo the same Australian/NZ Standard tests. The Australian/NZ Standard impact attenuation test, using this solid Mg-headform, does not consider the effect of the human head deformation. The stiff foam liner transfers impact energy directly to the cranium, as the liner will not crush.

Irrespective of the type of headform used in trials, researchers have concluded that helmet liners should be less stiff and ideally be made of lower density foam to absorb impact forces rather than transfer the forces to the cranium vault. Corner *et. al.* (1987) recommended a softer liner of about 30kg/m^3, rather than the density of 50 kg/m^3 (used at that time), and also reported that a lower density foam, being lighter, would reduce rotational acceleration. The densities recommended by researchers are between 25 kg/m^3 (Hope and Chinn, 1989) to 30-32 kg/m^3 (Corner *et. al.*,1987; Mills and Gilchrist, 1990).

However it would not be appropriate to design a motorcycle helmet employing a foam layer entirely of low-density foam. Such a helmet liner would be too soft for heavier collisions and would not be sufficiently durable to provide a reasonable life for the helmet. Ideally a helmet will incorporate properties of both strength and energy absorbtion. To pass the stringent Australian/NZ Standards, the impact-energy-absorbing liner must crush in a non-linear way, i.e. from lower densities to higher densities, increasing in stiffness as crushing continues.

1.2 New Technology:

A new shock-absorbing liner for helmets has been designed to reduce fatality and brain contusions by absorbing and dissipating the impact of forces. The new design incorporates low-density foam embedded, in a unique configuration, into the currently used high-density foam. In this research the dual-density configuration extends halfway throughout the thickness of the foam samples with densities from 20-30 kg/m^3 to 70-80 kg/m^3. This configuration should also occur in the vulnerable temporal region. Rotational acceleration and whiplash on the wearer's neck should also be reduced, as the helmet is less dense and lighter. It is possible to produce a variety of liners for helmets, with different density combinations, for various purposes, e.g. child and adult bicycle helmets to professional motorcycle helmets. A **dual-density liner** combining low and high density foams in a particular configuration could reduce the proven safety deficiencies of the currently used **single-density** hard-stiff foam liners.

1.3 Aims

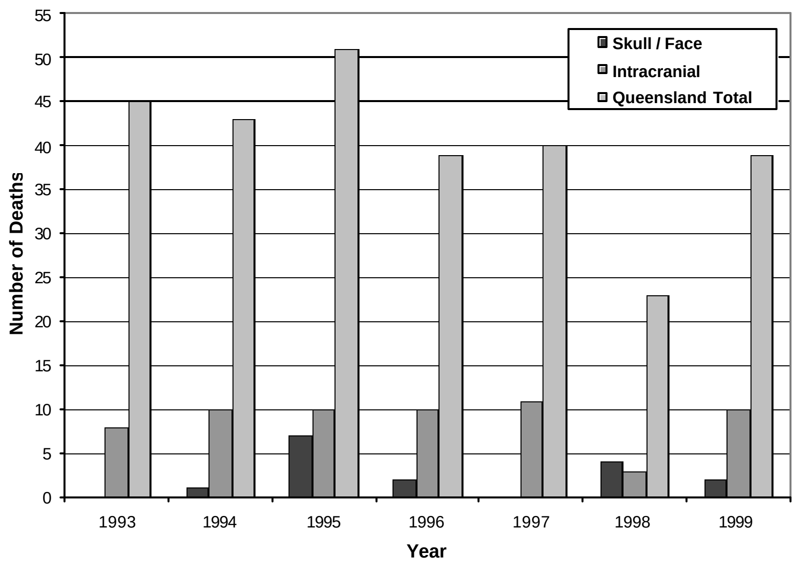
This project is the first stage in the development of a prototype for the new shock absorbing liner for motorcycle and bicycle helmets. This research requires the design and manufacture of a tool in which flat polystyrene-foam samples, with an area of 15x15cm^2 and a thickness of 3.5-4.0cm can be produced, and then tested under the requirements of the Australian/NZ Standard (AS1698 and AS/NZ2063).

The aims are to:

- develop an improved shock absorbing foam liner for motorcycle and bicycle helmets; and

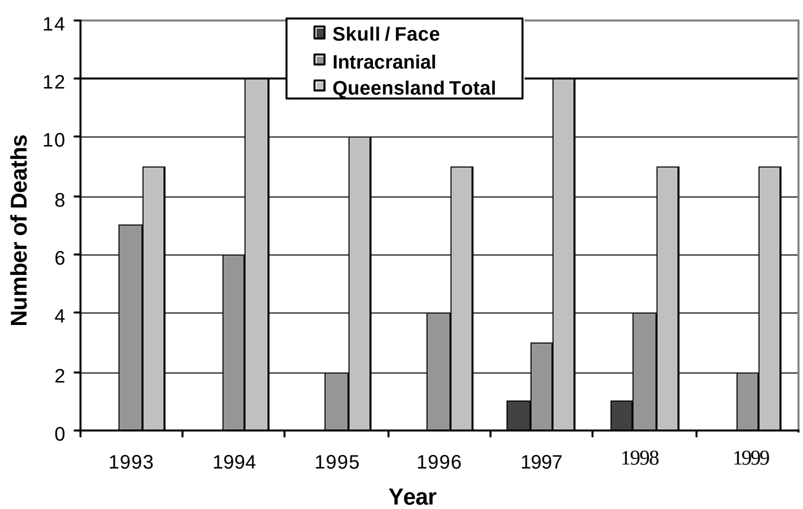
- demonstrate that the newly designed shock absorbing foam liners will absorb an impact force more effectively than the hard foam liners currently used, i.e. more crushing, less slab cracking, longer time duration during crushing and peak deceleration below 300g's.

Figure 1.0: **Motorcycle Deaths from Head Injuries**
(Queensland Transport)



[Note: heading fonts for Figs 1.0 & 1.1 are inconsistent with rest of report.]

Figure 1.1: **Bicycle Deaths from Head Injuries**
(Queensland Transport)



1.4 Outcomes of the Project

The project is divided into five stages:

Stage 1

- Plan and manufacture the special tool to produce newly designed dual density foam samples;
- Production of flat foam samples including the current design of single density and the new design of dual density.

Stage 2, (Test 1)

- Testing of flat foam samples to Australian/NZ Standards;
- Analyzing of Test 1 results;
- Modification and production of flat foam liners for Test 2.

Stage 3, (Test 2)

- Testing of flat foam samples to Australian/NZ Standards;
- Analysis of Test 2 results;
- Modification and production of flat foam samples for Test 3.

Stage 4, (Test 3)

- Testing of flat foam samples to Australian/NZ Standards; and
- Analysis of Test 3 results.

Stage 5

- Analysis and interpretation of all tests results; and
- The writing of the final report.

2.0 METHOD

2.1 The Australian/NZ Standards

The impact test for both the motorcycle (AS 1698) and bicycle (AS/NZS 2063) helmets involves a series of controlled impacts where a helmet is placed over a Mg-headform, and then dropped in a guided free fall through described heights (1.5m and 1.83m) onto a flat steel anvil. Trials are conducted on headforms of three different sizes and mass, corresponding to small, medium and larger helmet sizes. The headform, used in this project, approximates the shape of an adult human head and weighs 3402g, and with the support assembly 5109g. Located at the centre of gravity of the headform is the accelerometer, which measures the vertical deceleration upon impact (peak g-force transferred to the headform).

The manufactured, flat-foam samples were taped onto various hard surfaces (flat steel anvil, concrete, bitumen and kerb channeling) with masking tape, rather than onto the Mg-headform. The latter was difficult and may have produced inconsistent results. The Mg-headform with its attached assembly is dropped onto the foam sample.

2.1.1 Motorcycle Helmets

Four motorcycle helmets are impacted twice at four sites for the Australian Standard. Two sites are impacted by dropping the headform from a height of:

- 1.83m onto a flat steel anvil with an impact speed of 6.0m/s; and
- 1.385m onto a hemispherical anvil with an impact speed of 5.2m/s.

For this research, only the first test with a drop height of 1.83m was required to make a comparison of the crushing of the single-density and dual-density flat foam samples. The g-force acceptable to the Australian Standard for motorcycle helmets, in a double impact at a drop height of 1.83m, is 300 +/- 15g.

The four motorcycle helmets are exposed to four environmental conditions for a period of 4 - 24 hours. These are:

- cold temperature of -5^{o}C;
- ambient temperature between 18-25^{o}C;
- hot temperature of 50^{o}C; and
- sprayed or immersed in water at ambient temperature.

The environmental conditions were applied to this project.

The Australian Standard also requires motorcycle helmets to withstand a penetration test. A steel conical striker with a mass of 3kg is dropped from 3m onto a helmet fitted headform. The helmet will only pass this test if the point of the penetrator does not make contact with the magnesium headform. It is believed that the conical striker would not penetrate the carbon/kevlar-fibre shell fused to the flat foam samples. Only in the next stage of the prototype development will this test be required.

2.1.2 Bicycle Helmets

For the Australian/NZ Standard, eight bicycle helmets are subjected to four impact tests per helmet, where each helmet is impacted at four sites only once. The helmets are dropped (from 1.5m) on a flat steel anvil at an impact speed of 5.4m/s. The eight helmets tested are exposed to the same environmental conditions as outlined above for motorcycle helmets, except two bicycle helmets are tested for each condition. The maximum acceptable g-force for bicycle helmets is 300 +/- 15g. The flat dual-density foam liners have been tested at drop heights of 0.5m, 1.0m and 1.5m.

A localised test is applied instead of the penetration test for bicycle helmets. In this case a 20mm rounded v-shaped anvil is dropped from a height of 1m onto any part of the helmet fitted headform. This test will not be performed on the flat foam liners in this project.

The testing procedure in this research is summarized in Table 2.1.

Table 2.1. Test Procedure Carried Out on Each Type of Foam.

Sample No. - Test type	**Impact Surface**	**Environment**	**Drop Height (m)**
1 - Bicycle	flat anvil	ambient	0.50
2 - "	flat anvil	ambient	1.00
3 - "	flat anvil	ambient	1.50
4 - "	flat anvil	cold	1.50
5 - "	flat anvil	hot	1.50
6 - "	flat anvil	wet	1.50
7 - "	bitumen	ambient	1.50
8 - "	concrete paver	ambient	1.50
9 - "	kerb channel	ambient	1.50
10 - "	road based soil	ambient	1.50
11- Motorcycle	flat anvil	ambient	1.83
12 - "	flat anvil	cold	1.83
13 - "	flat anvil	hot	1.83
14 - "	flat anvil	wet	1.83
15 - "	bitumen	ambient	1.83
16 - "	concrete paver	ambient	1.83
17 - "	kerb channel	ambient	1.83
18 - "	road based soil	ambient	1.83
19 spare or repeat			
20 spare or repeat			

For each sample, the following measurements were recorded:

- peak deceleration (g-force);
- deceleration time during impact (ms);
- average thickness before crushing (mm);
- thickness of the maximum compressed zone (mm);
- crushing of liner (mm), i.e. the difference between the average thickness before crushing and thickness of the maximum compressed zone, and
- the long and short axis of the elliptical-shaped depression caused by the impact of the Mg-headform (mm).

For each sample, a brief description of the type and amount of cracking was recorded.

2.2 Stage 1

The project involved contracting a foam manufacturing company, Rmax Rigid Cellular Plastics, to plan, design and manufacture an innovative new tool. The same company used this tool to successfully produce flat samples of foam incorporating the new design. The new design enabled low density foam (e.g. 30 kg/m^3), of a particular configuration, to be embedded into the liner of high density foam (e.g. 70 kg/m^3). A newly developed foam-processing procedure, using the special tool, was established to manufacture foam samples of dual density, which proved to be more complicated than earlier contemplated.

A fibreglass manufacturer was also contracted to manufacture carbon/kevlar-fibre shells, which were applied to the backs of foam samples. Testing of these samples simulated the Australian Standard for motorcycle helmets, whereas foam samples without the shell-backing simulated foam liners used in bicycle helmets.

The first batch of foam samples, to be tested in Stage 2, consisted of two types:

- Twenty samples of dual density foam (i.e. 70/30 kg/m^3) of size 15cm x 15cm x 4.0 cm.
- Twenty samples of single density foam (i.e. 70 kg/m^3) of same size.

2.3 Stage 2 (Test 1)

Each type of foam was tested in accordance with the standards outlined in Section 2.1. Each type of foam was impacted onto different hard and/or rigid surfaces, e.g. bitumen, concrete paver, kerb channel and road base soil, under varying environmental conditions.

Samples were sorted in relation to similar mass. All foam samples were labeled according to date tested, foam type, test condition and mass (e.g., 6/11, A1, hot, 60.5 g). Tests (1,2 and 3) on foam samples were carried out by Imtest Laboratory Ltd. in Christchurch New Zealand and the procedure adopted for testing each type of foam is outlined in Table 2.1.

All samples tested were retained and returned to Brisbane for further analysis. The results of Test 1, from Stage 2, were analysed regarding the optimum performance for the newly designed dual density foam. From these results, it was possible to determine which densities provided the greatest crushing whilst still conforming to the Australian/NZ Standards. Following the analysis of Test 1 results, modified foam samples were manufactured for Test 2.

The modification stage involved the production of two types of foam. The first type consisted of:

- Over forty samples of dual density foam (i.e. 75/30 kg/m^3) of size 15cm x 15cm x 4.0cm;
- Over twenty samples of single density foam (i.e. 75 kg/m^3) of same size.

2.4 Stage 3 (Test 2)

Twenty one modified dual-density foam samples were tested by impacting the less dense side of the sample, and then another nineteen similar samples were impacted on the reverse side. This was carried out to determine which side would be best suited for positioning against the human cranium. Nineteen single-density foam samples were then tested to compare against the dual-density foam samples.

The modified samples, in this stage, were also tested to the Australian/NZ Standards, as per Stage 2 including the use of Table 2.1.

Test 2 results and samples were analysed. A third batch of foam samples was ordered and manufactured for Test 3. The major concern was the consistency of crushing, impact times and g-forces. The third batch included:

- Forty dual-density foam samples (twenty 75/30 kg/m^3 and twenty 75/25 kg/m^3) ; and
- Twenty single-density foam samples (75 kg/m^3).

Four leftover dual-samples (75/30 kg/m^3) and four single-foam samples (75 kg/m^3) from Stage 2, thickness of 2.5 cm were also prepared for Test 3 in Stage 4.

2.5 Stage 4 (Test 3)

The dual-density and single-density foam samples described in Stage 3 were tested to the Australian/NZ Standards, as per Stage 2, and the results analysed.

On completion of Test 2 and Test 3 all samples were retained and returned to Brisbane for further analysis.

2.6 Stage 5

This Stage involved the analysis of all three tests for 161 flat samples of foam (i.e. 100 samples with new design and 61 samples with current design) and the writing of the final report.

The analysis of each Test included the comparison of the:

- amount of cross-sectional and elliptical-shaped depression of crushing;
- amount and type of cracking in the foam;
- peak g-force; and
- impact time in ms.

3. 0 RESULTS

A total of 161 flat samples of foam (i.e. 100 samples with new design and 61 samples with current design) were tested and analysed as part of the project. The majority of the samples were of the same dimensions and fabricated from small-expanded polystyrene (EPS) foam bead. Only eight samples were 2.5 cm thick whereas the majority were 3.5-4.0 cm thick.

Table 3.1, p10, outlines the number, foam type and label of samples, their quoted manufacturers densities, thickness of foam slab and average mass for each test. It contains the quoted manufacturers densities for the single and dual-density foam liners; these densities may vary between 60 - 80 kg/m^3 (for 70 kg/m^3 foams) and between 65 - 85 kg/m^3 (for 75 kg/m^3 foams).

It is important to note that the foam manufacture, Rmax, stated that the foam densities produced are within +/- 10 kg/m^3 from their quoted density. Therefore it can be presumed that the single-density foam samples used for each test are of the same density in which the lower density is embedded within the dual-density foam sample liners. This means there is consistent comparison between the two types of foam liners. It is important to note that comparisons should not be made between batches prepared on different dates for different Tests. The densities of the single foam samples are not similar across the batches.

All the results determined by the Australian/NZ Standards testing by Imtest are given in the Appendix. The following Table 3.0 summarizes these results.

Table 3.0: Summary of Results within the Appendix

Appendix / Table	Test	Foam Results
1 / 1	1	A1
1 / 2	1	B1
2 / 1	2	A2
2 / 2	2	A2R
2 / 3	2	B2
3 / 1	3	A3
3 / 2	3	A4
3 / 3	3	B3
4 / 1	3	A2M
4 / 2	3	B2M

All dual-density foams are denoted by the capital letter "A" and the single foam samples by "B". The letter "R" denotes the impact occurring on the reverse side, i.e. the impact occurs on the denser side of the dual-density foam liners. The letter "M" represents the smaller slab-thickness (2.5 cm) of the foam liners.

Table 3.1: Outline of Foam Samples Tested.

No. of Samples tested (name)	Foam Type	Manufacturers quoted Densities (kg/m ^{3})	Approx. Thickness (cm)	Average Mass (g)	Test
11 (A1)	dual	70/30	3.5 – 4.0	55.4 (sd = 6.8)	1
9 (A1)	dual / backing	70/30	3.5 – 4.0	87.3 (sd = 4.5)	1
13 (A2)	dual	75/30	3.5 – 4.0	61.2 (sd = 1.2)	2
8 (A2)	dual/ backing	75/30	3.5 – 4.0	134.1 (sd = 5.8)	2
11 (A2R)	dual	75/30	3.5 – 4.0	61.9 (sd = 1.1)	2
8 (A2R)	dual/ backing	75/30	3.5 –4.0	130 (sd = 2.9)	2
10 (A3)	dual	75/25	3.5 – 4.0	64.0 (sd = 0.4)	3
8 (A3)	dual/ backing	75/25	3.5 – 4.0	147.0 (sd = 11.1)	3
10 (A4)	dual	75/30	3.5 – 4.0	62.8 (sd = 0.2)	3
8 (A4)	dual/ backing	75/30	3.5 – 4.0	149.6 (sd = 3.4)	3
11 (B1)	single	70	3.5 – 4.0	67.9 (sd = 2.1)	1
9 (B1)	single/ backing	70	3.5 – 4.0	96.1 (sd = 1.2)	1
11 (B2)	single	75	3.5 – 4.0 PE	70.1 (sd = 0.2)	2
8 (B2)	single/ backing	75	3.5 – 4.2 PE	143.0 (sd = 4.2)	2
10 (B3)	single	75	3.5 – 4.0 PE	70.0 (sd = 0.7)	3
8 (B3)	single/ backing	75	3.5 – 4.0 PE	126.8 (sd = 11.8)	3
3 (A2M)	dual	75/30	2.5 – 3.0	58.0 (s.d = 0.1)	3
1 (A2M)	dual/ backing	75/30	2.5 – 3.0	94.1	3
3 (B2M)	single	75	2.5 – 3.0	69.8 (sd = 0.1)	3
1 (B2M)	single/ backing	75	2.5 – 3.0	98.4	3

The letter R indicates the samples were tested in reverse.
The letter M indicates the modified samples were thinner than the majority of foam samples.
The letter PE indicates the samples were post expanded.

4.0 DISCUSSION

This topic is divided into four sections related to the measurements of:

(i) crushing,
(ii) time duration,
(iii) peak deceleration, and
(iv) cracking.

Each section displays tables for Tests 1, 2 and 3 for different impacting surfaces and different environment conditions. The gray shading in each table indicates where the newly designed foam samples performed as well as or better than the single density foam samples.

4.1 Crushing

The cross-sectional maximum crushed thickness of the foam-slab and the elliptical-shaped depression of the foam caused by the impacting Mg-headform represent the crushing of the foam sample.

4.1.1 Cross-Sectional Maximum Crushed Thickness of Foam Samples from Various Drop Heights.

The amount of crushing of foam samples with new design (dual-density) and current design (single-density) at various drop heights (m) is shown in Table 4.1 and Figure 4.1 (a, b and c). The tests were carried out in an environment at ambient temperature and used a flat steel anvil as the impacting surface.

Table 4.1: Crushing of Foam Samples at Various Drop Heights.

Foam Sample	Crushing (mm) at Drop Heights (ambient, flat anvil)			
Density (kg/m^3)	0.50 m	1.00 m	1.50m	*1.83m
A1 70/30	5.6	7.4	8.4	13.6
B1 70	2.0	5.2	7.6	11.9
A2 75/30	4.6	6.4	7.3	11.3
A2R 75/30	4.6	5.9	7.5	10.6
B2 75	3.5	4.8	6.3	12.5
A3 75/25	5.8	7.0	9.3	16.7
A4 75/30	5.8	7.9	8.9	16.4
B3 75	5.2	6.0	8.0	16.0

*** Double Impact occurs at 1.83m**

Under impacts from the Mg-headform from drop heights of 0.5m to 1.83m, the dual-density foam samples crushed better than the harder and stiffer single-density foam liners (Figure 4.1a, b and c).

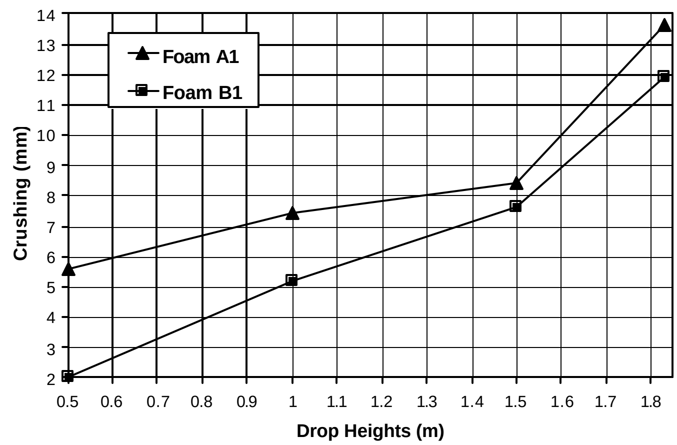
The average increase in the cross-sectional crushing is 1.5 mm. This equates to a mean increase of 4.3% crushing of the foam liner slab-thickness for bicycle helmets (from 0.5 to 1.5m drop height).

The first-impact crushing measurement, at a drop height of 1.83m, was not recorded, as the Australian/NZ Standard for motorcycles requires a double impact. Figure 4.1 displays a considerable increase in crushing for a drop height of 1.83m following the double impact standard test. The percentage increase in crushing, of the dual density foam, compared to the single density foam for a drop height of 1.83m is 4.6%. One exception occurs in Test 2 (Figure 4.1b), where higher crushing occurs for the single-density foam sample. These samples are inconsistent because they were post-expanded with poorly fused beads of foam and generally all showed cracking through the slab thickness. Post expanded foam samples are generally thicker and the increase in crushing is due to the density of the foam being less than was intended. The percentage of slab-crushing of the single-density foam, calculated from post extended slab-thickness, is less than the percentage slab-crushing of the dual density liner (Appendix 5). This implies that the dual-density foam crushed better than the post-expanded foam liners.

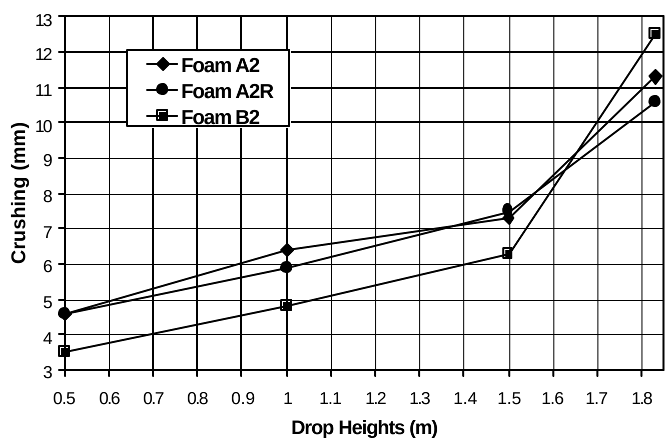
When the dual-density foam samples were reversed so that the Mg-headform impacted the denser side of the samples (A2R), the total crushing was reasonably similar to that of the dual-density foam liner. This involved the Mg-headform colliding with the less dense side of the foam liner (A2) (Figure 4.1b).

Figure 4.1: Crushing of Foam Samples at Various Drop Heights (Flat Anvil Surface and Ambient Temperature) (Double Impact occurs at 1.83m)

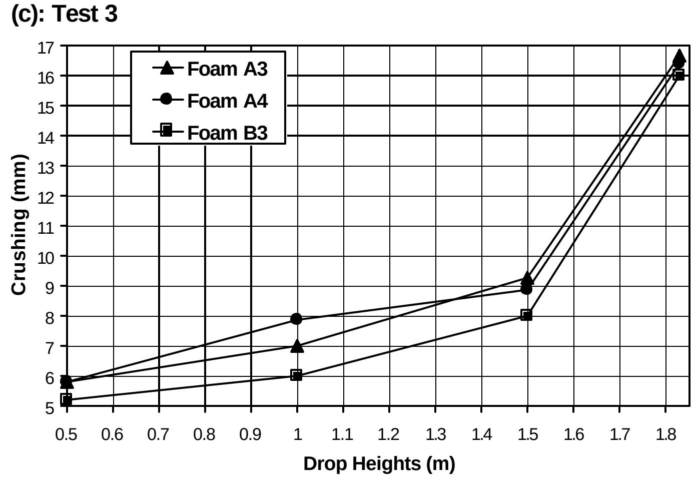
(a) Test 1



(b): Test 2



(c): Test 3



4.1.2 Cross-sectional Maximum Crushed Thickness from Impacting on Various Hard Surfaces.

The results showing the amount of crushing of foam samples, by dropping the magnesium headform from various heights onto samples of foam positioned on different impacting surfaces, are shown in Table 4.2 (a and b) and Figure 4.2 (a, b and c).

Table 4.2a: Tests 1 and 3 results showing the amount of crushing for different samples of foam on various impacting surfaces.

Impacting Surface	Drop Height (m)	Crushing of foam Samples (mm) A1	B1	A3	A4	B3
Flat anvil	0.50	5.6	2.0	5.8	5.8	5.2
Flat anvil	1.00	7.4	5.2	7.0	7.9	6.0
Flat anvil	1.50	8.4	7.6	9.3	8.9	8.0
Bitumen	1.50	6.0	7.1	8.8	8.6	8.0
Concrete	1.50	8.1	7.7	9.0	9.0	7.0
Road base	1.50	5.5	4.4	6.5	6.7	6.3
Kerb channel	1.50			12.0	11.8	11.4
Flat anvil	1.83	13.6	12.4	16.7	16.4	16.0
Bitumen	1.83	8.2	9.0	12.8	12.4	11.2
Concrete	1.83	9.9	8.5	12.9	12.7	9.5
Road base	1.83	6.5	6.8	12.2	12.0	9.6
Kerb channel	1.83			12.4	13.0	10.7

The results from Test1 and Test3 (Table 4.2a, Figure 4.2a and c), generally indicate that samples of foam made of dual-density crushed more than the samples of foam made of single-density for various impacting (impacted) surfaces. The reason for the reverse effect for bitumen and the road base, in test 1, may be due to both surfaces absorbing some of the impact energy, however this was not repeated in Test 3. The Test 1 bitumen and road base results are inconsistent.

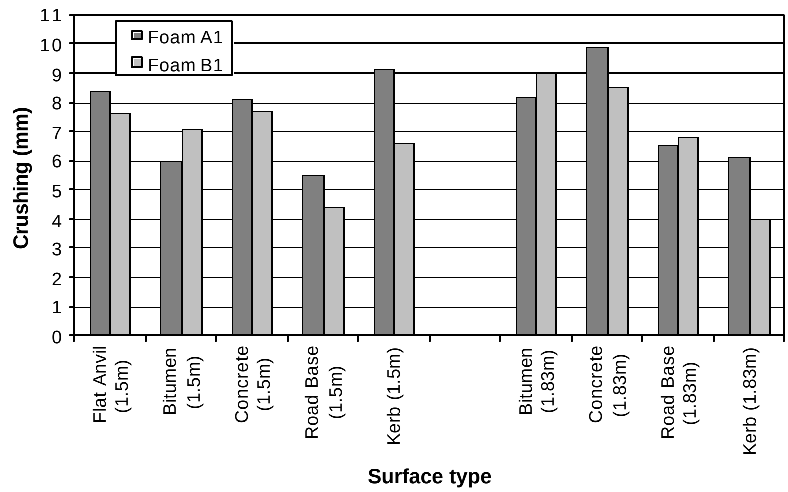
Table 4.2b: Test 2 results showing the amount of crushing for different samples of foam on various impacting surfaces.

Impacting surface	Drop Height (m)	Crushing of foam Samples (mm) A2	A2R	B2
Flat anvil	0.50	4.6	4.6	4.0
Flat anvil	1.00	6.4	5.9	4.9
Flat anvil	1.50	7.3	7.5	6.6
Bitumen	1.50	8.8	7.2	7.5
Concrete	1.50	8.5	7.3	7.5
Road base	1.50	6.1	6.4	4.2
Flat anvil	1.83	11.5	10.6	12.7
Bitumen	1.83	9.1	7.1	8.6
Concrete	1.83	8.3	7.0	8.4
Road base	1.83	7.3	5.9	7.8

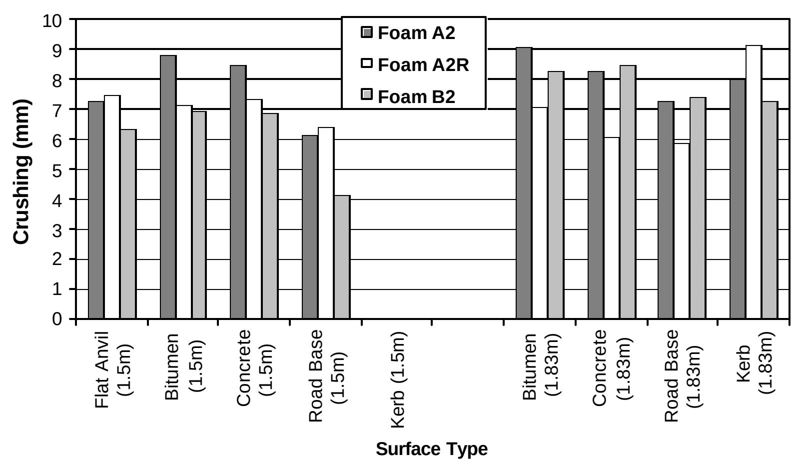
For the results from Test 2 (Table 4.2b and Figure 4.2b), it is obvious that dual-density samples (A2) generally crushed more than single-density samples (B2) and generally crushes better than the reverse impacting of the dual-density foam samples (A2R).

Figure 4.2: Crushing of Foam Samples against Various Surfaces (Ambient Temperature)

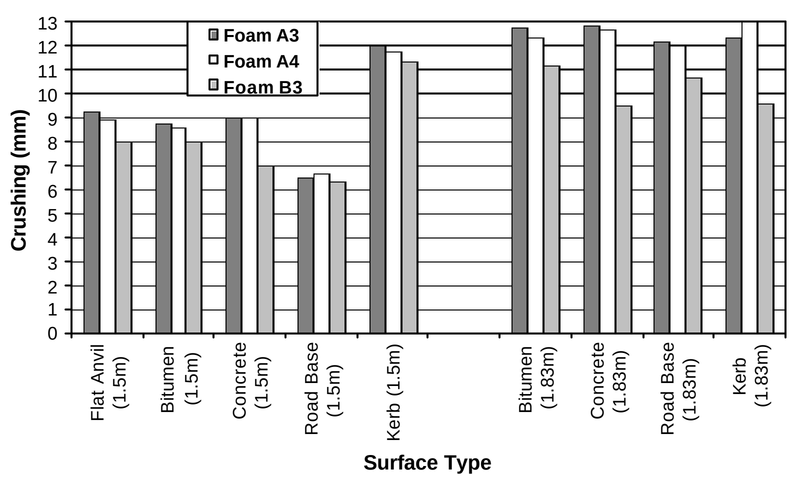
(a) Test 1



(b): Test 2



(c): Test 3



The result obtained for road base is probably a little unreliable as the initial compaction of the road base material may vary from test to test. This may explain the conflicting results indicated in the two dual-density samples of A2 and A2R.

An interesting situation occurs for the dual-density foam impacted on the reverse side (A2R), when impacted at a drop height of 1.83m on hard surfaces. The more dense side of the liners crack when impacted by the Mg-headform, rather than deform inwards. This inhibits crushing and results in lower crushing values than those obtained for the single-density foam samples. Under a drop height of 1.5m, the reversed dual-density liners behaved much like the single-density foam liners, with very similar crushing results.

4.1.3 Crushing Foam under Various Environmental Conditions

The impact results on foams which had been subject to varying environmental conditions are presented in Table 4.3 (a and b) and Figure 4.3 (a, b and c). The results from Test 1 and 3, presented in Table 4.3a and Figure 4.3 (a and c), demonstrate that all conditioned foam samples (i.e. ambient, cold, hot and wet) made of dual density foam crushed better than the samples made of single density foam.

Table 4.3(a): Crushing of Different Foam Samples Conditioned under Various Environments, Tests 1 and 3.

Environmental Condition	Drop Height (m)	Crushing of foam Samples (mm) A1	B1	A3	A4	B3
Ambient	0.50	5.6	2.0	5.8	5.8	5.2
Ambient	1.00	7.4	5.2	7.0	7.9	6.0
Ambient	1.50	8.4	7.6	9.3	8.9	8.0
Cold	1.50	8.9	7.4	8.4	8.8	7.2
Hot	1.50	10.1	7.0	8.6	8.7	6.6
Wet	1.50	7.8	6.5	9.3	8.9	7.2
Ambient	1.83	13.6	12.4	16.7	16.4	16.0
Cold	1.83	12.3	11.4	15.8	15.7	14.3
Hot	1.83	13.6	12.7	16.4	16.6	13.3
Wet	1.83	13.3	12.3	17.5	16.7	15.3

Table 4.3(b): Crushing of Different Foam Samples Conditioned under Various Environments, Test 2.

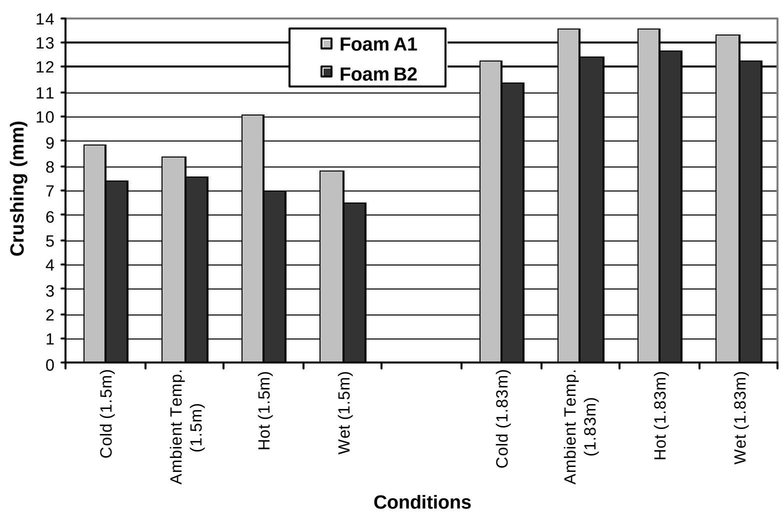
Environmental Condition	Drop Height (m)	Crushing of foam Samples (mm) A2	A2R	B2
Ambient	0.50	4.6	4.6	4.0
Ambient	1.00	6.4	5.9	4.9
Ambient	1.50	7.3	7.5	6.6
Cold	1.50	7.3	7.4	7.4
Hot	1.50	8.2	7.8	7.1
Wet	1.50	8.9	7.7	7.9
Ambient	1.83	11.5	10.6	12.7
Cold	1.83	11. 9	9.7	13.5
Hot	1.83	12.8	11.4	13.4
Wet	1.83	12.3	10.8	13.1

Generally the results from Test 2, presented in Table 4.3b and Figure 4.3b, display that the dual-density foam liners (A2) crushed more than the same foam samples impacted on the reverse side (A2R) under a drop height of 1.83m, when the foam samples were conditioned for cold, ambient, hot and wet conditions. However, the responses to impacting the dual-density foam liners, A2 and A2R, at the drop height of 1.5m are virtually the same for cold, ambient and hot temperatures. The wet dual-density foam (A2) showed slightly more crushing than A2R and B2.

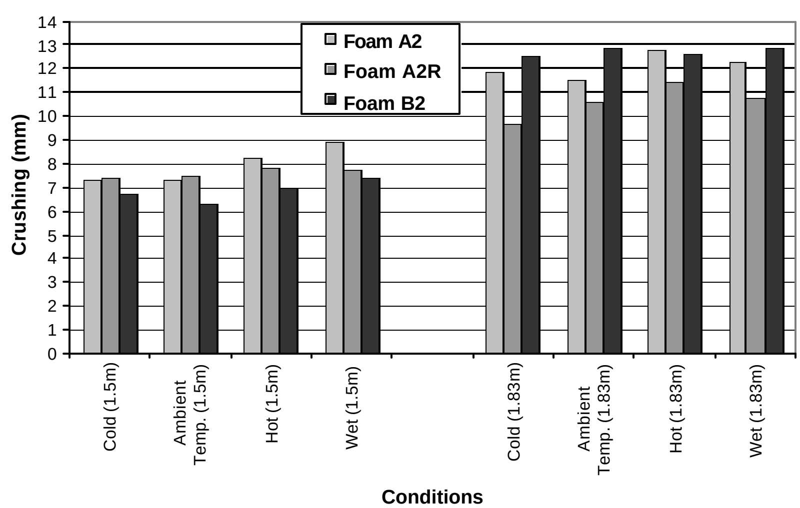
As for impacting over various hard surfaces in Test 2, the conditioned single-density foam samples gave conflicting results in crushing. Few samples out-crushed the newly developed dual-density foam samples. The single-density foam samples were post-expanded during their production, being lighter, less dense than they should be (and less than the single density liners from Test 1 and 3) and having a raised surface in the center of the sample. The density of the single-density samples merged closer to the densities of the dual-density foam samples. Also under further inspection, the foam beads within the single-density foams did not fuse well during their production. Cracks did not occur through the beads as they should have, but formed around the beads demonstrating poor quality control during their manufacture.

Figure 4.3: Crushing Foam under Various Environmental Conditions (Flat Anvil Surface)

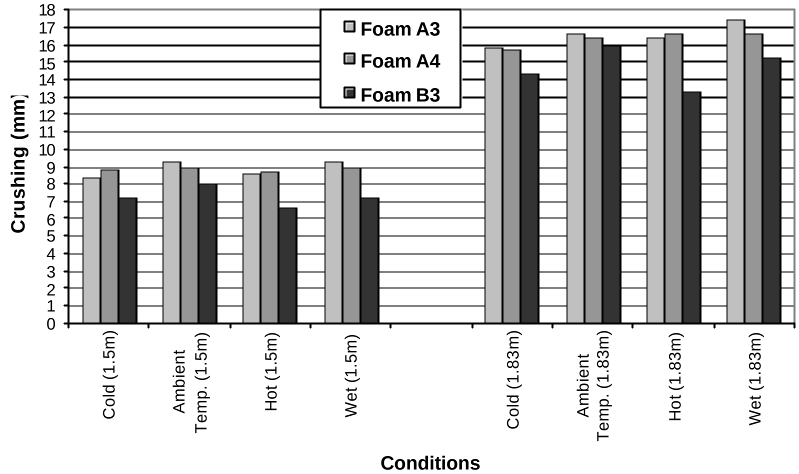
(a) Test 1



(b) Test 2



(c) Test 3



4.1.4 Elliptical-Shaped Impact Depression within Foam Samples caused by the Mg-Headform.

The Mg-headform created an elliptical-shape impact depression within the foam. Two measurements were used to resolve the dimensions of this shape, i.e. the long and short axis. The long axis was formed due to the Mg-headform rebounding sideways. The short axis did not show this rebounding effect, and is therefore the more accurate reflection of the effects of the elliptically formed depression. When the rebounding did not move sideways, the elliptical nature of the depression was near circular. In any situation, the short axis reflected the only true and consistent representation of the dimension of the impact depression.

Table 4.4 (a, b, c and d) and Figure 4.4 (a, b and c) display the short axis of the depression within the foam sample and the drop height of the headform. As the drop height increases, the short axis of the depression in the foam also increases. This is due to the increase of absorption of impact energy.

The dual-density foams, in Tests 1, 2 and 3, have larger and deeper impact depressions than do single-density foam liners. Figure 4.4 (a, b and c), confirms a greater width of crushing and this is consistent with the results obtained for cross-sectional crush thickness. The dual-density foam samples give an average increase in short axis of 1 cm (~ 10%) more than the single-density foam liner. One single-density foam liner (Figure 4.4a) shows a discrepancy at drop height 1.83m, which may be explained by the sample's post-expanded nature and cracking.

The two dual-density foam samples, A3 and A4, follow roughly similar elliptical crushing as their combined dual densities are very close, i.e. 75/25 and 75/30 kg/m^3 (Figure 4.4c).

Table 4.4a: Test 1 and 3 results showing the width of crushing at short axis for different samples of foam for different conditions and various impacting surfaces(tested to pedal cycle standard)

Impacting Surface/condition	Drop Height (m)	Width of crushing at short axis (mm) A1	B1	A3	A4	B3
Flat anvil/ambient	0.50	91	75	81	80	70
Flat anvil/ambient	1.00	103	90	90	94	86
Flat anvil/ambient	1.50	111	109	100	102	93
Flat anvil/cold	1.50	108	104	104	101	92
Flat anvil/hot	1.50	111	104	109	102	95
Flat anvil/wet	1.50	108	103	103	104	94
Bitumen/ambient	1.50	115	110	107	106	93
Concrete/ambient	1.50	128	106	103	106	94
Road base/ambient	1.50	104	84	93	100	89
Car pillar/ambient	1.50	115	92	-	-	-
Kerb channel/ambient	1.50	-	-	77	76	59

Table 4.4b: Test 1 and 3 results showing the width of crushing at short axis for different samples of foam for different conditions and various impacting surfaces(tested to motorcycle standard)

Impacting Surface/condition	Drop Height (m)	Width of crushing at short axis (mm) A1	B1	A3	A4	B3
Flat anvil/ambient	1.83	115	119	113	111	106
Flat anvil/cold	1.83	112	107	111	114	102
Flat anvil/hot	1.83	120	113	110	114	104
Flat anvil/wet	1.83	119	116	109	115	103
Bitumen/ambient	1.83	106	100	108	111	92
Concrete/ambient	1.83	112	102	104	107	95
Kerb channel/ambient	1.83	87	74	88	94	83
Road base/ambient	1.83	102	94	106	103	88

Table 4.4c: Test 2 results showing the width of crushing at short axis for different samples of foam for different conditions and various impacting surfaces (tested to bicycle standard)

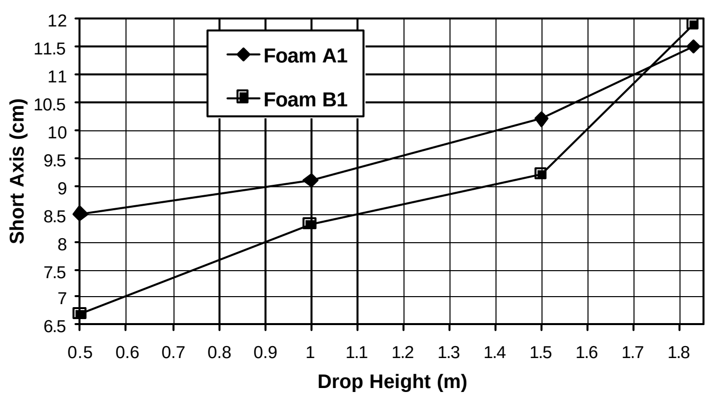
Impacting Surface/condition	Drop Height (m)	Width of crushing at short axis (mm) A2	A2R	B2
Flat anvil/ambient	0.50	81	71	74
Flat anvil/ambient	1.00	96	83	87
Flat anvil/ambient	1.50	105	90	94
Flat anvil/cold	1.50	102	90	93
Flat anvil/hot	1.50	103	90	92
Flat anvil/wet	1.50	105	86	91
Bitumen/ambient	1.50	102	91	93
Concrete/ambient	1.50	103	91	90
Road base/ambient	1.50	103	80	85
Kerb channel/ambient	1.50	-	-	63

Table 4.4d: Test 2 results showing the width of crushing at short axis for different samples of foam for different conditions and various impacting surfaces (tested to motorcycle standard)

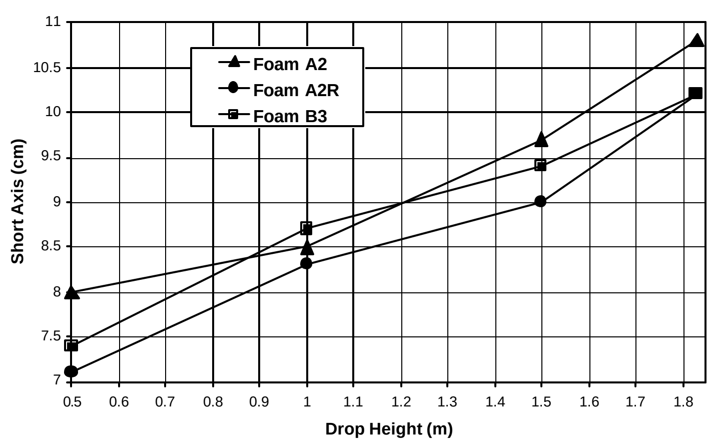
Impacting Surface/condition	Drop Height (m)	Width of crushing at short axis (mm) A2	A2R	B2
Flat anvil/ambient	1.83	108	102	102
Flat anvil/cold	1.83	108	100	102
Flat anvil/hot	1.83	107	101	104
Flat anvil/wet	1.83	112	101	102
Bitumen/ambient	1.83	99	92	94
Concrete/ambient	1.83	104	93	94
Kerb channel/ambient	1.83	90	75	84
Road base/ambient	1.83	94	92	94

Figure 4.4: Elliptical Depression and Drop Height (Flat Anvil Surface and Ambient temperature)

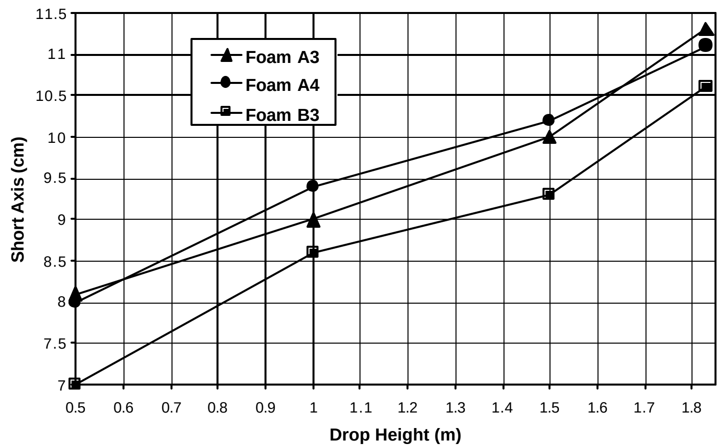
(a) Test 1



(b) Test 2



(c) Test 3



4.1.5 Findings for Crushing:

- Samples of foam, from Test 1, with dual-densities 70/30 kg/m^3 (A1) clearly showed more crushing than samples with single density 70 kg/m^3 (B1).

- Samples of foam, from Test 2, with dual densities 75/30 kg/m^3 (A2) and samples of foam with same dual density, but reversed (A2R) generally crushed more than samples with single density 75 kg/m^3 (B2).

- Samples of foam, from Test 2, with dual densities 75/30 kg/m^3 (A2) showed roughly similar crushing to samples with same dual densities but reversed (A2R) for drop heights of 1.5m, and cold to ambient temperatures.

- Samples of foam, from Test 3, with dual-densities 75/30 kg/m^3 (A3) and 75/25 kg/m^3 (A4) clearly showed more crushing than samples with single density 75 kg/m^3 (B3).

- Samples of foam, from Test 3, of dual-densities 75/30 kg/m^3 (A3) and 75/25 kg/m^3 (A4) have roughly similar crushing properties for drop heights of 1.5 -1.83 m.

- Hard surfaces of flat steel anvil, bitumen and concrete effect thickness crushing of foam in similar ways, where as road base gives higher and varied results dependant upon its compaction. Higher still are kerb channeling results as crushing occurs on both sides of the foam, i.e. crushing from the Mg-headform and metal kerb.

- Generally, cold (-5^{0}C), ambient (18-25^{0}C) and hot (50^{0}C) samples exhibit similar crushing effects, although hot and wet samples give slightly higher values of crushing. This may be due to hot expanded air spaces and water giving further absorbent properties to the foam, however these results are inconsistent and inconclusive.

4.2 Impact-Time Duration (Deceleration Time)

The impact-time duration occurs when the headform decelerates on collision with the foam sample. During impact, the headform is decelerated by the force transmitted from the anvil surface through the thickness of the foam. It is the crushing and arc-cracking of the foam with the deflection of the carbon-kevlar shell (for those samples with a backing), which determines the deceleration time and the required stopping distance of the headform upon impact.

Ideally, foam samples that show an increase in crushing and less cracking will also exhibit an increase in the impact time duration (i.e. the time of interaction), resulting in the reduction of the impact force being translated through the foam to the headform (i.e. cranium vault for a motorcyclist and cyclist). In other words, in a real crash situation, it is preferable that the force of impact occurs over the longest possible time to improve the outcome of the motorcyclist and cyclist. It is desired that cracking does not occur, as this does not assist in the protection of the human cranium.

4.2.1 Impact-Time against Drop Height

From the results shown in Table 4.4 and Figure 4.5 (a, b and c), it is clear that the samples with dual density foam (i.e. A1, A2, A2R, A3 and A4) have a longer time duration than the samples with single density foam (i.e. B1, B2 and B3). These results are in agreement with the results given for crushing whereby an increase in crushing generally indicates an increase in the time duration.

In regard to the double impact from drop heights of 1.83m, it is also important to note that the time duration for the first drop is always greater than the time duration for the second drop. This is an indication that the foam crushes more on the first drop than the second drop and there is less energy-absorption capacity after the first drop. The samples of A2 also exhibit a greater time duration than the samples of A2R, as the more dense side of the dual-density foam samples are less absorptive than the less dense side of the foam, and react much like the single-density foams (B2).

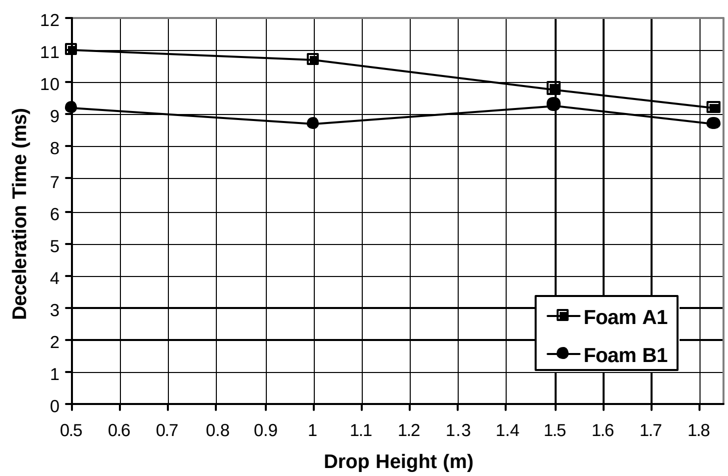
Table 4.4: Time duration for foam samples at various drop heights (m).

Foam Sample/ Density (kg/m^3)	**Average Impact Time Duration (ms)** 0.50 m	1.00 m	1.50m	1.83m
A1 70/30	11.0	10.7	9.8	1st 9.2 2nd 7.2
B1 70	9.2	8.7	9.3	1st 8.7 2nd 7.4
A2 75/30	10.0	10.7	11.0	1st 9.3 2nd 8.3
A2R 75/30	9.3	9.3	9.7	1st 9.0 2nd 8.0
B2 75	8.7	9.7	9.0	1st 9.0 2nd 7.3
A3 75/25	10.3	10.7	9.7	1st 9.0 2nd 8.0
A4 75/30	10.7	10.0	9.7	1st 9.0 2nd 8.3
B3 75	9.7	10.0	9.7	1st 8.7 2nd 7.7

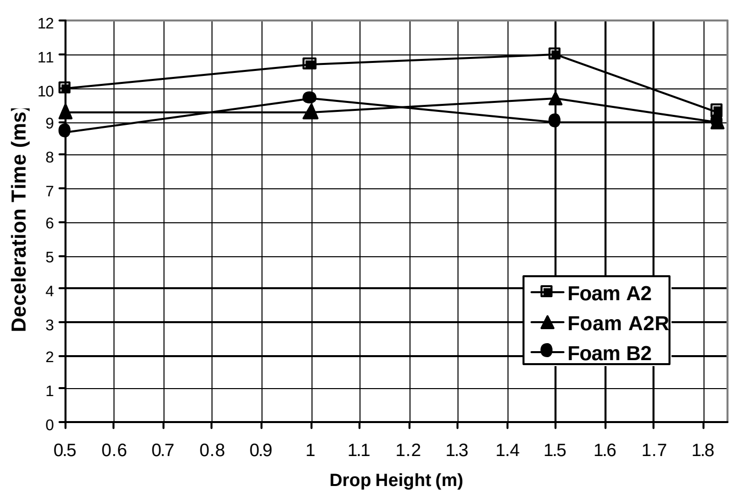
As the drop height increases, generating more impact force, the closer the deceleration times of the dual-density foams merges to the deceleration times of the single-density foams. Generally, the maximum improvement in impact-time with the dual-density foam samples, at a drop height of 1.5m, is 20% better than the impact-time of the single-density foam liner. This translates to approximately an extra 20% impulse (or force) that can be applied to a dual density liner compared to that which a single-density liner can suffer. At a drop height of 1.83m, an increase of over 5% occurs.

Figure 4.5: Impact Time against Drop Height
(Ambient Temperature and Flat Anvil Surface)

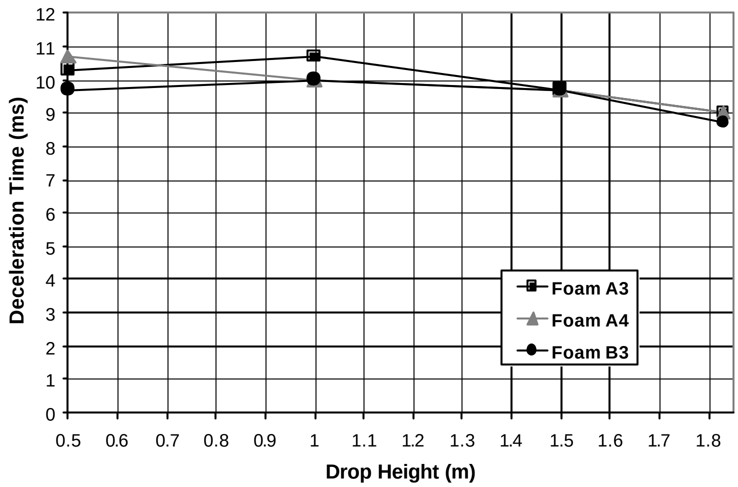
(a) Test 1



(b) Test 2



(c) Test 3



4.2.2 Impact-Time involved with Various Hard Surfaces

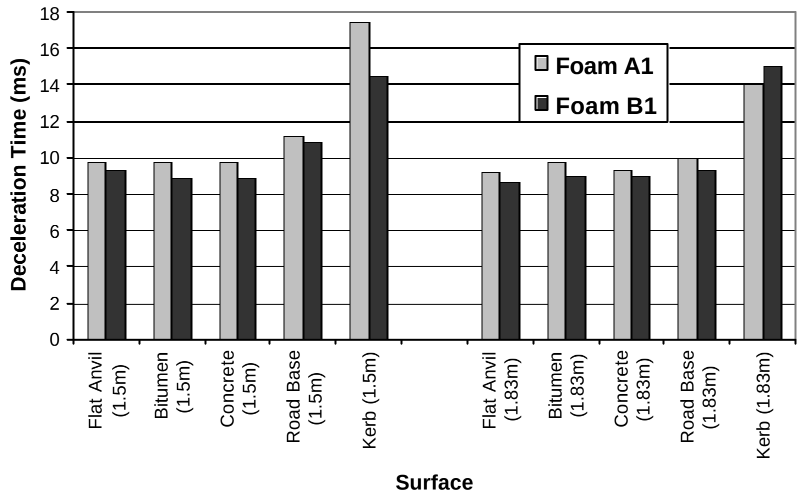
Table 4.5(a) and Figure 4.6 refer to the results obtained by impacting samples of foam on a variety of hard surfaces. Figure 4.6 clearly demonstrates that the dual density foams give longer impact-times than do single-density foams, when impacted on a variety of hard surfaces. Kerb channeling causes breaking and slab-cracking of single density foam samples more often, and these sometimes, especially for greater drop heights such as 1.83m, result in higher deceleration times (e.g. Tests 1 and 3).

Table 4.5(a): Tests 1 and 3 results showing the time duration for different samples of foam on various impacting surfaces.

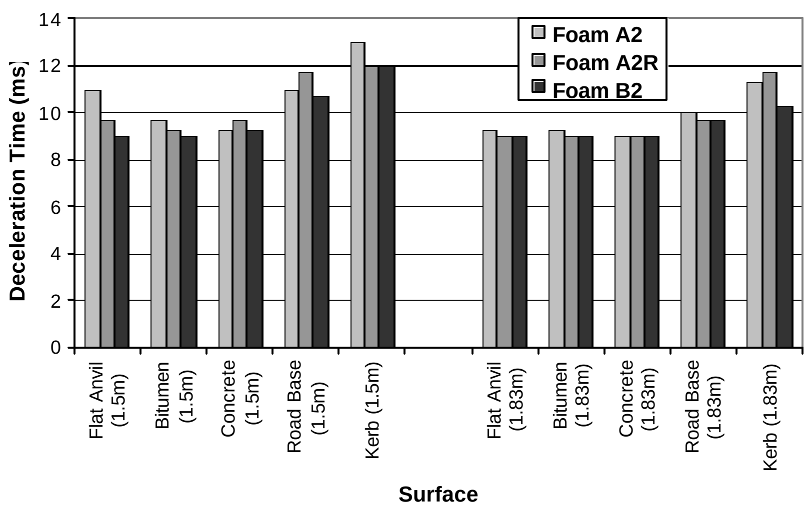
Impacting Surface	Drop Height (m)	Average Impact Time Duration of Foam Samples (ms) A1	B1	A3	A4	B3
Flat anvil	0.50	11.0	9.2	10.3	10.7	9.7
Flat anvil	1.00	10.7	8.7	10.7	10.0	10.0
Flat anvil	1.50	9.8	9.3	9.7	9.7	9.7
Bitumen	1.50	9.7	8.9	9.3	9.3	9.0
Concrete	1.50	9.7	8.9	9.0	9.0	8.7
Kerb Channel	1.50	17.5	14.5	11.7	13.3	10.3
Road base	1.50	11.2	10.9	10.0	10.0	9.3
Flat anvil	1.83	1st 9.2 2nd 7.2	1st 8.7 2nd 7.4	1st 9.0 2nd 8.0	1st 9.0 2nd 8.3	1st 8.7 2nd 7.7
Bitumen	1.83	9.7	9.0	9.3	9.3	9.3
Concrete	1.83	9.3	9.0	9.0	9.0	9.3
Kerb Channel	1.83	14.0	15.0	10.7	10.0	13.3
Road base	1.83	10.0	9.3	9.3	9.3	9.3

Figure 4.6: Impact Time against Various Impact Surfaces (Ambient Temperature)

(a) Test 1



(b) Test 2



(c) Test 3

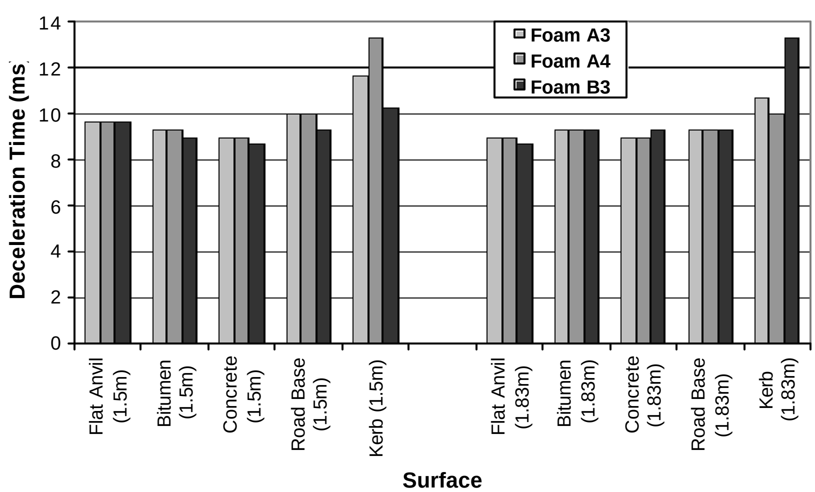


Table 4.5(b): Test 2 results showing the time duration for different samples of foam on various impacting surfaces.

Impacting surface	Drop Height (m)	Average Impact Time Duration of Foam Samples (ms) A2	A2R	B2
Flat anvil	0.50	10.0	9.3	8.7
Flat anvil	1.00	10.7	9.3	9.7
Flat anvil	1.50	11.0	9.7	9.0
Bitumen	1.50	9.7	9.3	9.0
Concrete	1.50	9.3	9.7	9.3
Kerb Channel	1.50	13.0	12.0	12.0
Road base	1.50	11.0	11.7	10.7
Flat anvil	1.83	1st 9.3 2nd 8.3	1st 9.0 2nd 8.0	1st 9.0 2nd 7.3
Bitumen	1.83	9.3	9.0	9.0
Concrete	1.83	9.0	9.0	9.0
Kerb Channel	1.83	11.3	11.7	10.3
Road base	1.83	10.0	9.7	9.7

Dual-density foam samples results (Figure 4.6b) indicate that foams, A2, generally have a greater impact-time than impacts on the reverse side (A2R), however, both of these generally have longer impact-time duration than that of the single-density foam samples (B2). The single-density foams, in Test 2, being post-expanded with unfused beads and raised surface, demonstrate inconsistent results, giving longer, equal or slightly less deceleration times than times obtained for dual-density foam liners.

Hard surfaces, consisting of flat steel anvil, concrete and bitumen, give reasonably consistent equal impact-times over drop heights of 1.5m and 1.83m (Figure 4.6). The road base allows some varying compaction, and kerb channeling results in the foam to be crushed on both sides of the foam (i.e. one surface by the Mg-headform and the opposite surface by the metal kerb) resulting in greater impact-times.

4.2.3 Impact-Time under Different Environmental Conditions

Table 4.6a and Figure 4.7 (a, b and c), of Tests 1, 2 and 3, generally illustrate that the dual-density foam samples exhibit similar or slightly longer impact-times than do single-density foam liners. The different environmental conditions generate little effect on impact times. Warmer foams exhibit expanded air pockets, which may assist absorption of impact energy. Colder foam exhibits properties of more dense foams. Water in wet foam-voids also assists absorption of impact forces. However, these differences in conditions are not always reflected by impact-times.

The results for the time duration obtained from test 2 are summarized in Table 4.6b and Figure 4.7b. Both samples A2 and A2R were made of the same dual densities and A2R samples were impacted in the reverse position on the denser side of the foam. The results indicate that A2 samples generally have greater time duration than A2R, and both dual densities foam samples generally have longer time duration than the single density foam samples of B2.

Table 4.6 (a): Tests 1 and 3 results showing the time duration for different samples of foam conditioned under various environments.

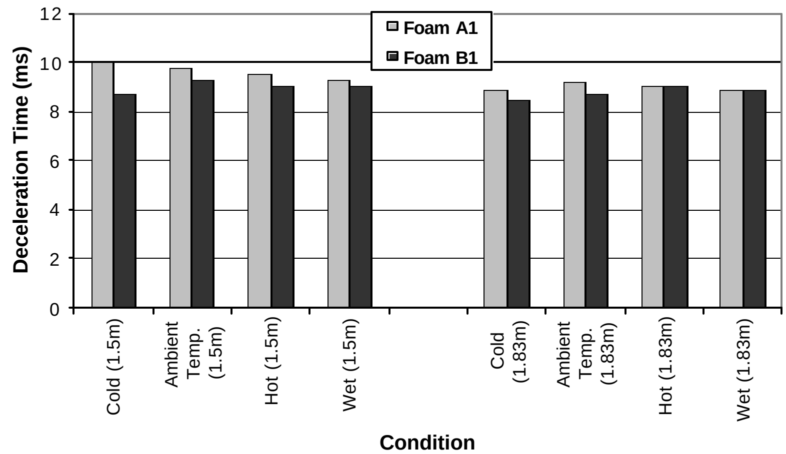
Environment Condition	Drop Height (m)	Average Time Duration of Foam Samples (ms) A1	B1	A3	A4	B3
Ambient	0.50	11.0	9.2	10.3	10.7	9.7
Ambient	1.00	10.7	8.7	10.7	10.0	10.0
Ambient	1.50	9.8	9.3	9.7	9.7	9.7
Cold	1.50	10.0	8.7	9.0	9.0	9.0
Hot	1.50	9.5	9.0	9.3	9.3	9.3
Wet	1.50	9.3	9.0	9.0	9.0	9.0
Ambient	1.83	1st 9.2 2nd 7.2	1st 8.7 2nd 7.4	1st 9.0 2nd 8.0	1st 9.0 2nd 8.3	1st 8.7 2nd 7.7
Cold	1.83	1st 8.9 2nd 7.4	1st 8.5 2nd 7.7	1st 8.7 2nd 7.7	1st 9.0 2nd 8.0	1st 8.7 2nd 7.7
Hot	1.83	1st 9.0 2nd 7.5	1st 9.0 2nd 8.5	1st 9.0 2nd 8.3	1st 9.3 2nd 8.3	1st 9.3 2nd 8.7
Wet	1.83	1st 8.9 2nd 7.7	1st 8.9 2nd 7.9	1st 9.3 2nd 8.0	1st 9.0 2nd 8.0	1st 9.3 2nd 8.3

Table 4.6 (b): Test 2 results showing the time duration for different samples of foam conditioned under various environments.

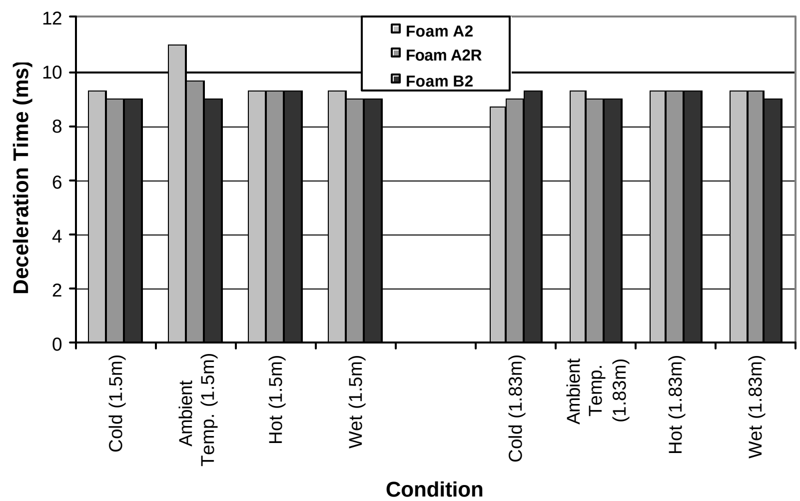
Environment Condition	Drop Height (m)	Average Time Duration of Foam Samples (ms) A2	A2R	B2
Ambient	0.50	10.0	9.3	8.7
Ambient	1.00	10.7	9.3	9.7
Ambient	1.50	11.0	9.7	9.0
Cold	1.50	9.3	9.0	9.0
Hot	1.50	9.3	9.3	9.3
Wet	1.50	9.3	9.0	9.0
Ambient	1.83	1st 9.3 2nd 8.3	1st 9.0 2nd 8.0	1st 9.0 2nd 7.3
Cold	1.83	1st 8.7 2nd 7.7	1st 9.0 2nd 7.7	1st 9.3 2nd 8.3
Hot	1.83	1st 9.3 2nd 8.0	1st 9.3 2nd 8.0	1st 9.3 2nd 8.7
Wet	1.83	1st 9.3 2nd 8.0	1st 9.3 2nd 8.3	1st 9.0 2nd 8.0

Figure 4.7: Impact Time under Varying Environmental Conditions (Flat Anvil Surface)

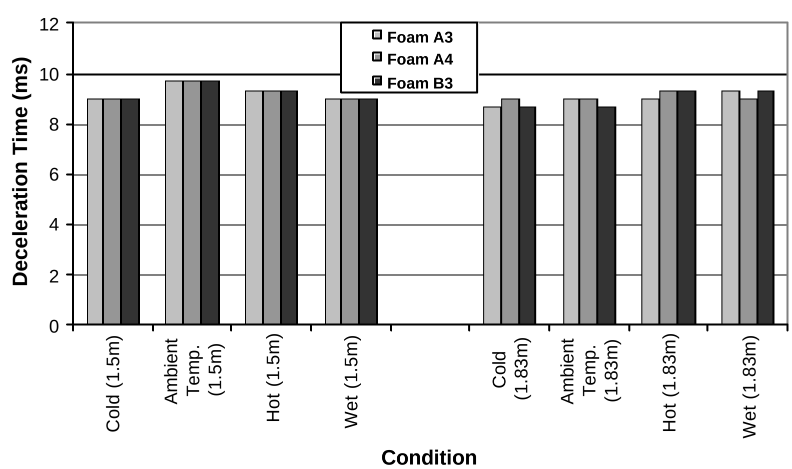
(a) Test 1



(b) Test 2



(c) Test 3



4.2.4 Findings for Impact-Time

- Samples of foam, from Test 1, with dual densities 70/30 kg/m^3 (A1) clearly had a longer time duration than samples with single density 70 kg/m^3 (B1).

- Samples of foam, from Test 2, with dual densities 75/30 kg/m^3 (A2) and samples of foam with same dual densities 75/30kg/m^3 but reversed (A2R) generally had a longer time duration than samples with single density 75 kg/m^3 (B2).

- Samples of foam, from Test 3, with dual densities 75/25 kg/m^3 (A3) and 75/30 kg/m^3 (A4) generally had longer time duration than samples with single density 75 kg/m^3 (B3).

- Samples of foam with dual densities 75/30 kg/m^3 (A2) generally had longer time duration than samples with same dual densities but reversed (A2R).

- Hard surfaces, such as flat steel anvil, bitumen and concrete, have reasonably similar impact-times for the same drop height, whereas road base gives higher results. Even higher results are obtained for kerb channeling impact-times, due to more crushing on both sides of the foam, i.e. crushing from the Mg-headform and metal kerb.

- Generally, cold (-5^{0}C) foam samples result in slightly lower impact-times than ambient temperatures (18-25^{0}C) for the same drop height. Hot (50^{0}C) and wet samples give slightly higher results for a drop height of 1.83m.

- Colder foams generally exhibit more dense-like properties.

- Hot and wet foam samples exhibit more energy absorbing properties for a drop height of 1.83m.

4.3 Impact Energy Attenuation (Peak Deceleration, g-force)

The peak deceleration is the peak g-force imparted to the Mg-headform by different foam samples positioned on various impacting surfaces. For each impact, the peak deceleration is measured in g-units and must not exceed the peak deceleration as set by the Australian Standards for both motorcycle and pedal cycle helmets. The maximum acceptable g-force, for both motorcycle and bicycle helmets, is 300g. The limit of uncertainty is given as +/- 15g. In this research, dual and single density flat-foam samples did not exceed the required g-force, and were well under it.

4.3.1 Impact Energy Attenuation caused by Various Drop Heights

As the drop height increases so does the g-force imparted to the Mg-headform (Table 4.7 and Figures 4.8 a, b and c). The dual-density foam samples, from Test 1, with the combined density of 70/30 kg/m^3, (A1 samples) generally demonstrated lower peak decelerations at drop heights from 0.5m to 1.5m (tested to bicycle standards) than single-density foam samples (Table 4.8a). This is not reflected in Test 2 and 3, where varied and conflicting results were obtained for the same drop heights (Table 4.8 a and c). This was also the case for all Tests at a drop height of 1.83m (the test for motorcycle standards). Refer to Table 4.8 (b and d).

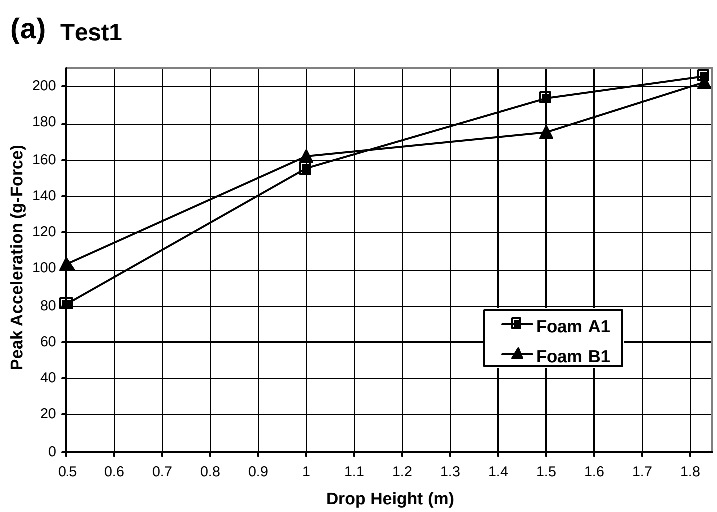
As stated previously, Test 2 and 3 single-density foams were post-expanded, foam samples B2 more than B3. This created a situation where the average densities of the new foam liner and the single density foams are too close for peak deceleration to be a distinguishable parameter. For a drop height of 1.83m, it was already noted that the crushing of the two types of foams were merging closer together, due to the effects of the hard unyielding Mg-headform. The peak decelerations of the single and dual density foams merged closer together, as is demonstrated in Figures 4.8 (a, b and c). This higher impact produces a compressed-denser foam of harder and stiffer properties, which is evident in the second impact, where peak decelerations were much higher, yet still conforming to the Australian/NZ Standards, i.e. < 300g's. The average density of dual-density foams in Test 1 are much lower than those in Tests 2 and 3. Therefore the range of average densities between the dual-density foam samples and single-density foams from Test 1, were greater than those in Test 2 and 3, which enabled the peak deceleration to be distinguished.

Another reason for the varied peak deceleration between the two foam samples is that the new configuration within the dual-density foam liner only extended halfway within the foam thickness. It is suggested that if the low-density configuration was extended to the full slab-thickness of the foam, it would produce lower average dual-density foam and therefore lower the peak deceleration compared to the currently used foam liner.

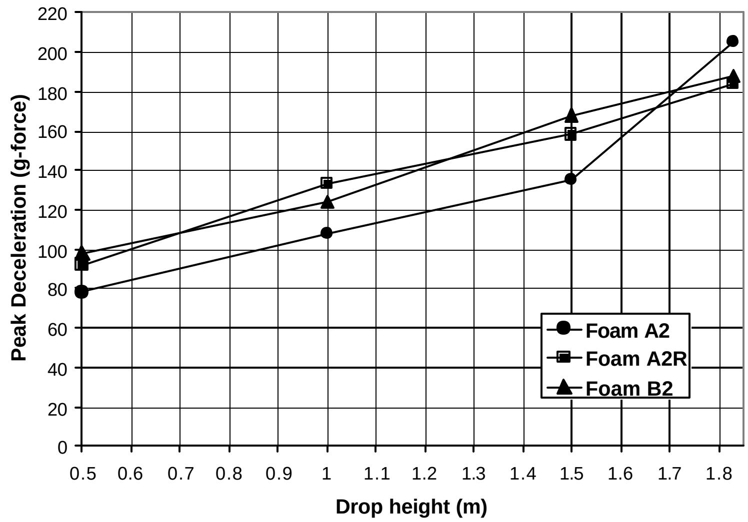
Table 4.7: Impact Energy Attenuation under Various Drop Heights (Ambient Temperature)

Foam Sample Density (kg/m^3)	Peak Deceleration (g-force) at Drop Heights (ambient, flat anvil) 0.50 m	1.00 m	1.50m	1.83m
A1 70/30	81	155	194	206
B1 70	103	162	175	203
A2 75/30	78	108	135	205
A2R 75/30	92	133	158	184
B2 75	98	124	168	188
A3 75/25	96	119	175	204
A4 75/30	94	143	178	202
B3 75	104	115	161	202

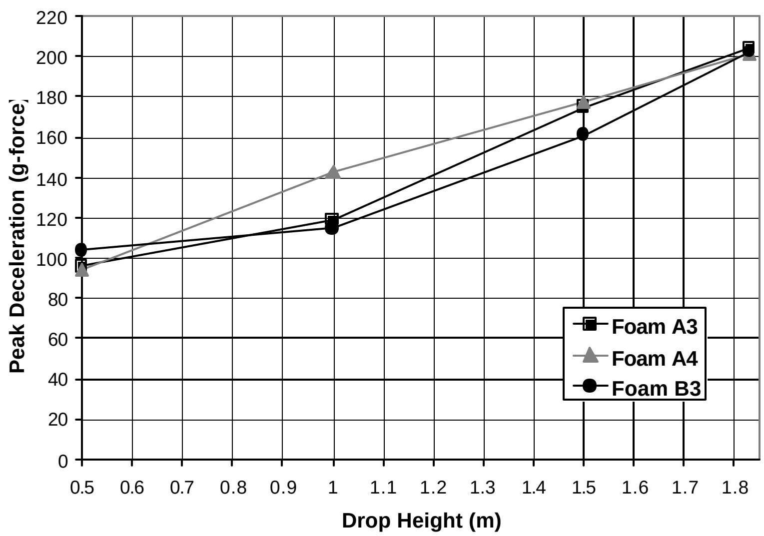
Figure 4.8: Impact Energy Attenuation against Drop Height (Flat Anvil Surface and Ambient Temperature)



(b) Test 2



(c) Test 3



4.3.2 Impact Energy Attenuation against Hard Surfaces

Table 4.8 (a, b, c and d) and its related Figure 4.9 (a, b and c) display peak deceleration from impacted foam, which were placed on various hard surfaces. Overall, hard surfaces such as flat steel anvil, concrete and bitumen result in roughly similar g-forces, when the Mg-headform is dropped from similar heights. In Test 1, bitumen compresses slightly more under impact by the headform compared to the unyielding characteristics of the steel anvil and concrete, as is demonstrated by its slightly lower peak deceleration. However, Test 2 and 3 give conflicting results.

At a drop height of 1.83m, for Tests 2 and 3, dual-density foam samples yield greater g-forces than single-density foams. In Test 1, these are generally reversed for drop heights of 1.5m, but similar for drop height of 1.83m.

Table 4.8a: Test 1 and 3 results showing the peak deceleration for different samples of foam for different conditions and various impacting surfaces, (tested to bicycle standard).

Impacting Surface/condition	Drop Height (m)	Peak Deceleration of foam Samples (g force) A1	B1	A3	A4	B3
Flat anvil/ambient	0.50	81	103	96	94	104
Flat anvil/ambient	1.00	155	162	119	143	115
Flat anvil/ambient	1.50	194	175	175	178	161
Flat anvil/cold	1.50	149	199	184	184	166
Flat anvil/hot	1.50	180	166	175	173	152
Flat anvil/wet	1.50	173	181	180	179	156
Bitumen/ambient	1.50	160	179	180	179	177
Concrete/ambient	1.50	165	176	182	182	166
Road base/ambient	1.50	124	127	141	151	155
Car pillar/ambient	1.50	98	106	-	-	-
Kerb channel/ambient	1.50	-	-	110	111	115

Table 4.8b: Test 1 and 3 results showing the peak deceleration for different samples of foam for different conditions and various impacting surfaces, (tested to motorcycle standard)

Impacting Surface/condition	Drop Height (m)	Peak Deceleration of foam Samples (g force) A1	B1	A3	A4	B3
Flat anvil/ambient	1.83	1st 206 2nd 286	1st 203 2nd 274	1st 204 2nd 265	1st 202 2nd 265	1st 202 2nd 265
Flat anvil/cold	1.83	1st 219 2nd 295	1st 215 2nd 277	1st 217 2nd 281	1st 215 2nd 278	1st 203 2nd 266
Flat anvil/hot	1.83	1st 206 2nd 285	1st 193 2nd 219	1st 203 2nd 266	1st 200 2nd 258	1st 163 2nd 216
Flat anvil/wet	1.83	1st 216 2nd 285	1st 200 2nd 245	1st 201 2nd 257	1st 201 2nd 259	1st 169 2nd 225
Bitumen/ambient	1.83	184	199	204	204	185
Concrete/ambient	1.83	203	199	204	200	182
Kerb channel/ambient	1.83	116	103	141	167	122
Road base/ambient	1.83	169	187	188	187	169

Table 4.8c: Test 2 results showing the peak deceleration for different samples of foam for different conditions and various impacting surfaces, (tested to bicycle standard)

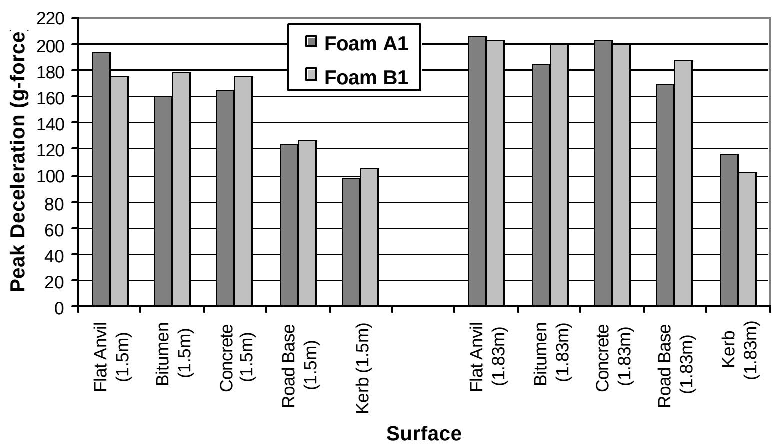
Impacting Surface/condition	Drop Height (m)	Peak Deceleration of foam samples (g force) A2	A2R	B2
Flat anvil/ambient	0.50	78	92	98
Flat anvil/ambient	1.00	108	133	124
Flat anvil/ambient	1.50	135	158	168
Flat anvil/cold	1.50	191	171	168
Flat anvil/hot	1.50	174	153	161
Flat anvil/wet	1.50	182	163	172
Bitumen/ambient	1.50	177	169	171
Concrete/ambient	1.50	185	174	168
Road base/ambient	1.50	128	114	139
Kerb channel/ambient	1.50	96	119	104

Table 4.8d: Test 2 results showing the peak deceleration for different samples of foam for different conditions and various impacting surfaces, (tested to motorcycle standard)

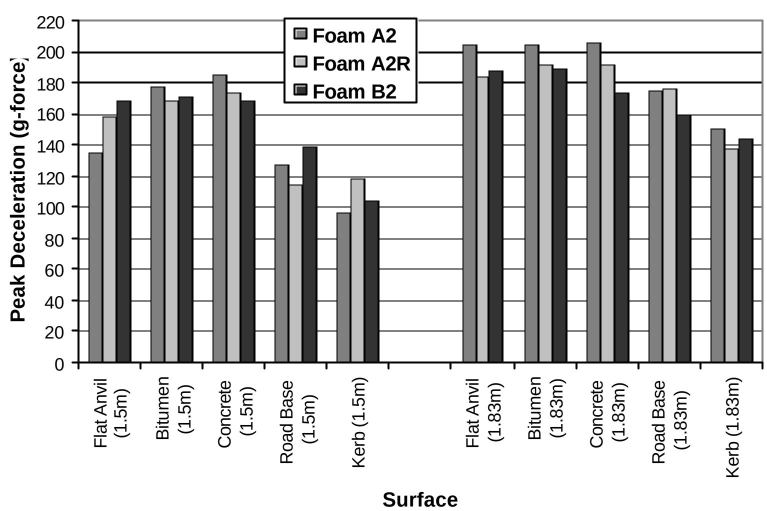
Impacting Surface/condition	Drop Height (m)	Peak Deceleration of foam samples (g force) A2	A2R	B2
Flat anvil/ambient	1.83	1st 205 2nd 268	1st 184 2nd 252	1st 188 2nd 243
Flat anvil/cold	1.83	1st 220 2nd 269	1st 208 2nd 250	1st 181 2nd 221
Flat anvil/hot	1.83	1st 201 2nd 253	1st 189 2nd 245	1st 167 2nd 220
Flat anvil/wet	1.83	1st 206 2nd 255	1st 190 2nd 236	1st 191 2nd 237
Bitumen/a mbient	1.83	205	191	189
Concrete/ambient	1.83	206	191	174
Kerb channel/ambient	1.83	151	137	144
Road base/ambient	1.83	175	176	159

Figure 4.9: Impact Energy Attenuation under Impact against Hard Surfaces (Ambient Temperature)

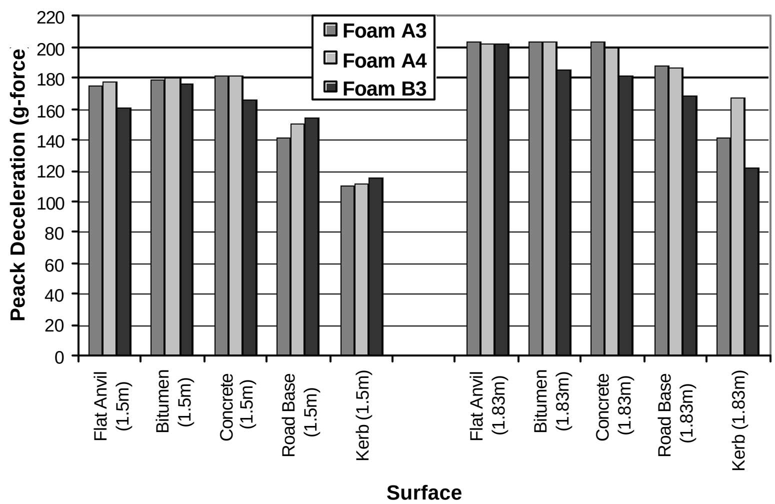
(a) Test 1



(b) Test 2



(c) Test 3

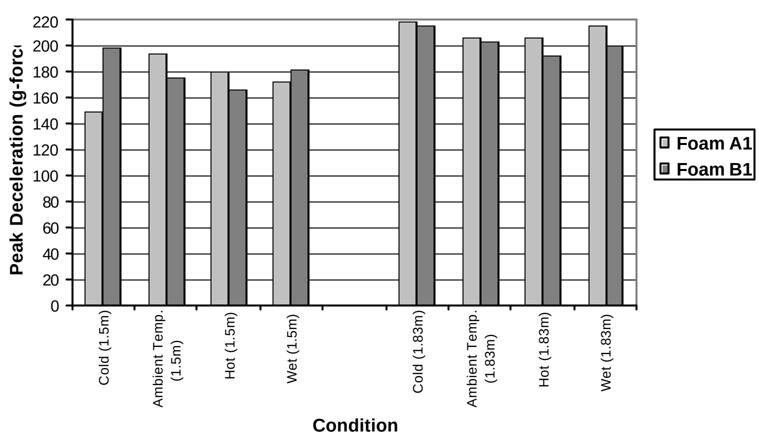


4.3.3 Impact Energy Atte nuation under a Variety of Environmental Conditions

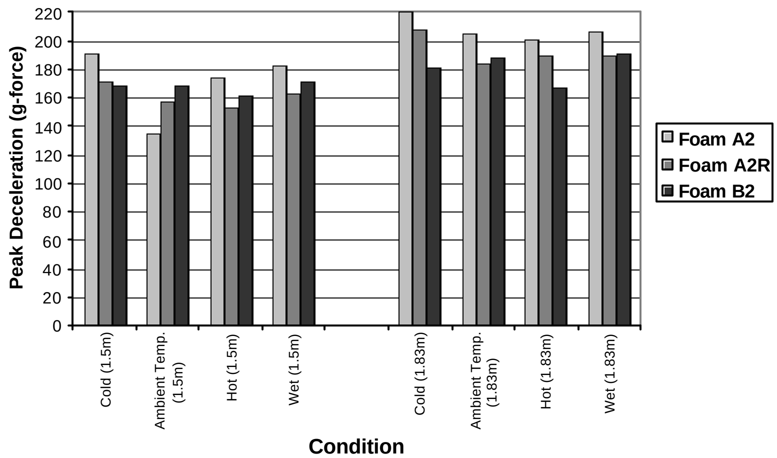
Generally, peak deceleration decreases slightly over an increase in temperature from -5^{o}C to 50^{o}C, (Figure 4.9 a, b and c). Under cold temperatures, based on g-force results and for the same drop height, the foam exhibits a more dense foam behavior than do warmer foams. Wet foams have similar g-forces as dry foams at ambient temperatures.

Figure 4.10: Impact Energy Attenuation under a Variety of Environmental Conditions (Flat Anvil Surface)

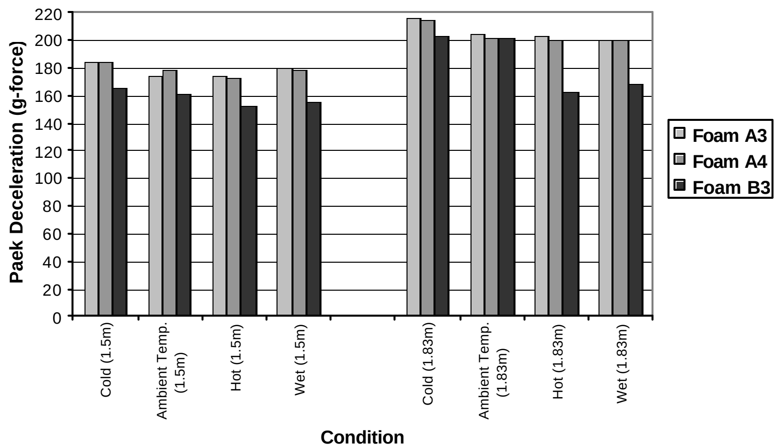
(a) Test 1



(b) Test 2



(c) Test 3



4.3.4 Findings of Impact Energy Attenuation

- All g-forces were within the requirements of the Australian/NZ Standards, i.e. being below 300g's.
- Samples of foam, from Test 1 with dual densities 70/30 kg/m^3 (A1) clearly showed lower peak decelerations than samples with harder single density 70 kg/m^3 (B1).
- Test 2 and 3 gave varied peak decelerations due to post-expanded single-density foam samples.
- Tests of impact on foams, for a drop height of 1.83m, result generally in higher g-forces than do those at lower drop heights.
- The second impact, of the double impact test at 1.83m, always generate higher g-forces than the first impact, indicating an already compressed/crushed and hence a more dense-like foam.
- Hard flat surfaces result in roughly similar g-forces.
- Road base and kerb channeling give lower values of g-forces, and bitumen displays a slight compression under impact.
- Generally, the g-forces decrease slightly over an increase in temperature from -5^{o}C to 50^{o}C.
- Wet foams have similar g-forces to that of dry foams at ambient temperature.

4.4 Cracking of foam under impact

As already stated, the amount of cracking exhibited by the samples of foam determines the time duration and the amount of force absorbed and imparted to the headform. In an impact situation involving a motorcycle or bicycle helmet, cracking through the thickness of the foam liner (slab-cracking) is undesirable as it renders the foam liner of the helmet useless in its ability to further absorb an impact force. As a result the foam is unable to distribute the focal impact over a larger area and to decelerate the blow at the point of impact.

The results, in the Appendices, demonstrate that for all three tests, the single density foam produced significantly more slab-cracking than the newly designed dual density foam especially when impacted from a drop height of 1.83 m.

The majority of cracking displayed by samples was in the shape of an arc outlining the spherical headform on impact. Arc-cracking has minimal effect, as it is part of the crushing process. However, cracks developing partly or fully through the thickness of the foam-slab renders it useless in crushing and absorbing impact forces. Slab-cracking of foam samples generally occurred for single-density foam at generally higher drop heights, whereas arc-cracking generally occurred for both single and dual density foam samples at drop heights of 1.83m. The most severe kind of slab-cracking occurred when samples of foam of both types (i.e. single and dual density) were placed on a kerb channel and impacted from heights of 1.5 m and 1.83 m. However, less of this type of cracking occurred for dual-density foams.

4.4.1 Findings on Cracking

- Samples of foam with single densities (70 kg/m^3, B1, and 75 kg/m^3, B2 and B3) tested to the Australian Standard for motorcycle and bicycle helmets all showed significantly more slab-cracking than samples of foam with dual densities (70/30 kg/m^3, A1, 75/25 kg/m^3, A3, and 75/30 kg/m^3, A2, A2R and A4).

4.5 Supplementary Tests

Two supplementary tests were carried out to assess the performance of the newly designed foam samples against the single density foam samples.

4.5.1 Foam Samples without Shell Backing Impacted at Drop Height of 1.83m.

The first test involved dropping the headform from a height of 1.83m onto samples of foam 75/30 kg/m^3 (A2 and A2R) and 75 kg/m^3 (B2) without carbon/kevlar fibre backings applied. The results for this test are shown in Table 4.9.

Table 4.9: Results from samples of foam without backing impacted from a height of 1.83m.

Samples Type	Peak Deceleration (g force)	Average Time Duration (ms)	% Crushing Of Liner	Width Of Crushing At Long Axis (mm)	Width Of Crushing At Short Axis (mm)	Cracking (tick)
A2 75/30 kg/m^3	1st 204 2nd 249	90 77	38.5	120	109	✓ slight arc
A2R 75/30 kg/m^3	1st 183 2nd Not tested	90	26.1	98	91	✓ slight arc
B2 75 kg/m^3	1st 178 2nd 233	90 ?	33.5	96 112	94 102	✓ arc

The results from Table 4.9 display that the foam sample of dual density (A2) crushed more than the sample with single density (38.5% compared to 33.5%) and the elliptical-shaped impact depression within the dual density foam sample was greater than that for the single density foam sample after two impacts. The sample that was impacted on the reverse side i.e. A2R showed less percent crushing and elliptical-shaped impact depression when compared with samples A2 and B2. This result was due to impacting the more dense side of the foam, which responds similarly to the single density foam. All three samples gave the same average time duration for the first impact and were all less than the required 300g-force. It is important to note that the dual density foam with no protective backing to help to spread the impact load is still more effective in absorbing an impact force from a greater height than the single density foam.

4.5.2 Foam Samples with Reduced Thickness Impacted at Various Drop Heights.

The second test involved reducing the thickness of the samples tested. This test involved dropping the headform from heights of 0.5m, 1.0m, 1.5m and 1.83m onto samples of foam 75/35 kg/m^3 (A2M, modified) and 75 kg/m^3 (B2M, modified) positioned on a flat steel anvil (Table 4.10).

Table 4.10: Results from samples of foam with reduced thickness impacted at various heights.

Sample Density (kg/m^3)	Drop Height (m)	Peak Deceleration (g force)	Average Time Duration (ms)	Crushing of Liner (mm)	Cracking (tick)
75/25	0.5	105	10.3	6.1	
75	0.5	99	9.7	5.3	
75/25	1.0	156	9.3	7.9	
75	1.0	144	9.0	7.1	
75/25	1.5	196	9.0	9.6	
75	1.5	177	9.0	8.8	
75/25	1.83	1st 216 2nd 323	1st 9.0 2nd 7.7	15.5	✓ arc
75	1.83	1st 200 2nd 272	1st 9.0 2nd 7.7	14.5	✓ arc

Table 4.10 clearly shows that the dual density foam samples with a reduced thickness exhibit greater crushing and time duration than the single density foam of similar thickness especially from lower drop heights. At a drop height of greater than 1.0m, the average time duration and crushing is similar. The second impact for the dual density exceeded the standard peak deceleration requirement of 300g's, which indicates the foam sample has been crushed to a thickness where most of the energy is being translated to the Mg-headform, and would not be suitable for motorcycle helmets.

4.6 Summary of Discussion

The stiffness and hardness of current helmet liners have been a consequence of the need to satisfy the stringent performance requirements contained in the Australian/NZ Standards. For Helmets to be certified to the Australian/NZ Standards, they must meet the requirements by passing two performance tests, the energy attenuation test and the penetration test. Both tests require the use of a solid Mg-headform, which represents only the shape of the human head.

This solid-rigid headform is capable of crushing hard-stiff foam liners in helmets, and manufacturers have had to provide high-density liners to pass the impact attenuation and penetration tests. In a worse case scenario, manufacturers have used 90 kg/m^3 polystyrene foam with a thickness of approximately 1.5cm to pass the test. In collisions, the human head is incapable of bending or compressing the foam and this is true for foam liners of 50 kg/m^3 used in Corner *et. al.* (1987) research. The "unyielding characteristics" of the Mg-headform is "quite inappropriate" and "rather artificial" as a simulation of the human cranium (Corner *et. al.*, 1987).

Mills and Gilchrist (1991), in their research into the effectiveness of foam liners in bicycle and motorcycle helmets, reported that "lower density foams can be used only if the impact test standards are rewritten with less emphasis on impacts with convex and pointed objects". Corner *et. al.* (1987) states that the attenuation and penetration tests with the Mg-headform fail to test protective-helmets in realistic crash situations.

In summary, the unyielding characteristic of the Mg-headform, used in both Australian/NZ Standards for motorcycle and bicycle helmets, easily crushes and compresses the currently used hard-stiff single-density foam liners. This would not be the case for impacts involving the human head. Corner *et. al.* (1987) showed, that when the Mg-headform was replaced by a humanoid headform (e.g. the Wayne State University, Hodgson headform) in impact-testing of helmets, little crushing and damage occurred to the hard-foam liners in helmets designed to the Australian/NZ Standards. The Hodgson headform does not generate the same level of cracking and crushing as the Mg-headform for stiff liners, but similar peak decelerations can occur because of flexing or inbending of the humanoid headform (illustrated in Figure 4.11).

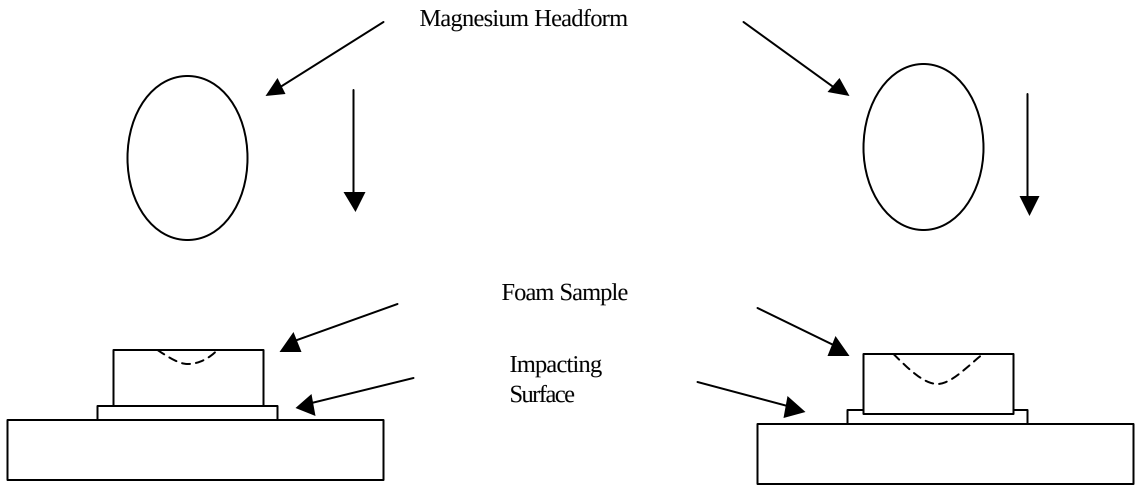
From previous experimental work (Corner *et. al.*, 1987), the indications are that the current helmet liners are too hard and stiff, and a foam liner of lower density should be used. The indication is that the newly designed, dual-density foam liners will respond more favourably than the single density foam liner, in a crash situation, by producing more crushing and less cracking, thereby preventing flexing or inbending of the head.

The Australian/NZ Standards for bicycle helmets do not consider the difference in the elastic deformation of a child's head. It is more deformable than adults' skulls. Previous research has indicated that a child's skull is more deformable than an adult's with very little difference by the age of 15 years (Mohan, Bowman, Snyder and Foust 1979). Corner *et. al.* (1987) carried out a series of bending tests on samples of adult's and children's skulls and found that the child's skull has a far greater flexibility, a reduced bending strength, and is far less protective of the brain than the adult skull. It is apparent that the foam liners currently used in children's helmets should be manufactured and tested differently from those for adult's helmets with the emphasis on lower density foam liners and improved shock absorption.

The newly developed dual-density liners provide an additional 5% for slab-thickness crushing and an increase of up to 20% deformation time, under Australian/NZ Standards testing. This provides a significant improvement in the protection offered by currently used helmets.

Figure 4.11

(a) The Australian/New Zealand Standard Impact Test for Motorcycle and Bicycle Helmets (Magnesium Headform).



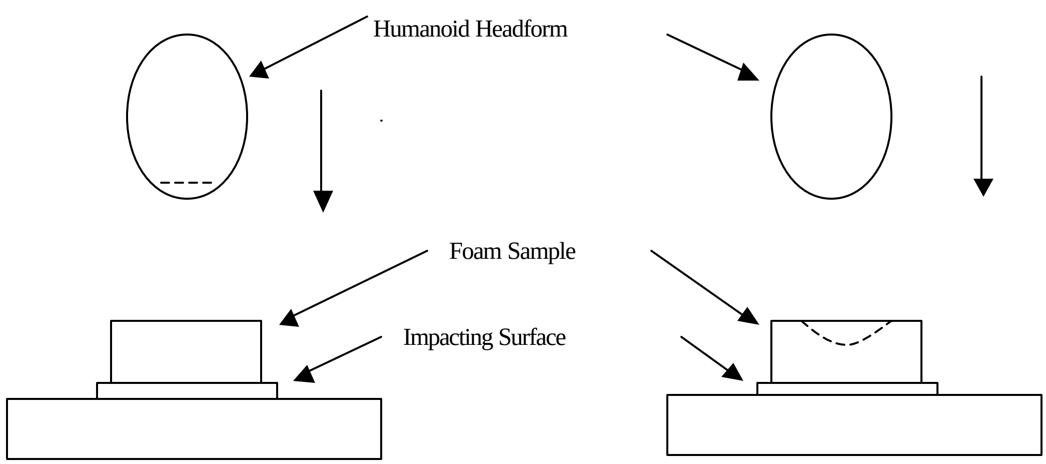
(i) Single density foam (i.e. current hard foam) shows:

- crushing
- cracking
- peak deceleration (< 300g's)

(ii) Dual density foam (i.e. newly designed foam) with the low density configuration extended to half the thickness of liner shows:

- greater crushing
- less cracking
- greater impact time duration
- varied peak deceleration (< 300g's)

(b) The Australian Standard Impact Test (Humanoid Headform)



(i) Research by Corner et al showed that single density foam (i.e. current hard foam) causes:

- deformation/inbending of humanoid headform
- similar peak deceleration to (i) above (<300 g's)

(ii) Proposed dual density foam (i.e. newly designed foam) with the low density configuration extended to include the whole thickness of the foam liner, is expected to show:

- more crushing
- less cracking
- greater impact time duration
- no deformation/inbending of humanoid headform
- peak deceleration (<300 g's) and lower than for (i) above.

5.0 CONCLUSION

The purpose of this research was to verify that the newly developed dual-density foam liners will absorb an impact force more effectively than the currently used hard single-density helmet liners. To achieve this an innovative engineered tool and a new processing procedure to manufacture flat samples of dual-density polystyrene foam-liners were developed.

The newly designed liner is comprised of a low-density foam embedded within a high-density foam in a unique configuration to half the foam thickness. This contrasts with the currently used helmet liners which incorporates only single high-density foam. The new dual-density foam liners, being less stiff and lighter in mass, also passed the stringent requirements of the Australian/NZ Standards for motorcycles and bicycles. Both types of foam samples gave readings for the peak deceleration below the required 300g's. For Test 1, the dual-density foam samples resulted in lower peak decelerations than for single-density foams. Tests 2 and 3 gave varied results. These results were mainly caused by the post-expansion of single-density foams from Tests 2 and 3.

The dual-density liners demonstrated improved shock-absorbing abilities. The analysis of each tests clearly showed that the newly designed foam samples outperformed the single-density foam liners by:

- 5% more slab-crushing;
- 10% extra elliptical-shaped depression within the foam;
- greater impact time duration (20%); and
- generally less slab cracking, than the current designed foam samples.

The results suggest that helmets incorporating the newly-designed shock-absorbing foam liner will absorb impact forces and energy and spread blows from the point of impact more effectively than the hard liners currently used in motorcycle and bicycle helmets. The new liners, being less dense and lighter, will also reduce rotational acceleration (Corner *et. al.*, 1987). The improvement in crushing, time duration and cracking is expected to translate into real crash situations. Accordingly the use of the dual density liner will result in a reduction in the number of head injuries and fatalities. The cost to the community will also be reduced.

6.0 RECOMMENDATIONS

- Extend the configuration of the low-density foam to include the whole thickness of the foam liner.

- Use densities in the range of 60-65/20-30kg/m^3 for the newly designed dual density liner.

- Conduct a series of tests involving a humanoid headform impacting samples of flat foam with new design to determine which side of the foam is more effective in absorbing an impact force.

- Develop prototypes for both motorcycle and bicycle helmets, incorporating the shock absorbing liner with new design and test both helmets to the appropriate Australian Standard.

- Test both prototype helmets using a humanoid headform with various impacting surfaces to obtain realistic crash results.

- Develop a special protective helmet for children incorporating the shock absorbing liner with the new design.

- Develop a new Australian/NZ Standard for testing the new child's protective helmet using a headform with similar physical properties of a child's cranium.

- High quality control in the manufacturing of the dual density foam is absolutely imperative in maintaining consistent densities.

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APPENDICIES

APPENDIX 1: RESULTS FROM TEST 1

Table 1: Results for foam type A1.

Samples No. Mass (g)	Impact Surface	Environ -ment	Drop Height (m)	Peak Deceler -ation (g force)	Average Time Duration (ms)	Thickness Before Crushing (mm)	Thickness At Base Of Crushing (mm)	Crushing Of Liner (mm)	Width Of Crushing At Long Axis (mm)	Width Of Crushing At Short Axis (mm)	Cracking (tick)
1 43.48	Flat Anvil	Ambient	0.5	81	11.0	34.5	28.9	5.6	9.1	8.5	
2 61.13	Flat Anvil	Ambient	1.0	155	10.7	34.6	27.2	7.4	10.3	9.1	
3 59.44	Flat Anvil	Ambient	1.5	194	9.8	34.6	26.2	8.4	11.1	10.2	✓ slight arc
4 46.56	Flat Anvil	Cold	1.5	149	10.0	34.7	25.8	8.9	10.8	10.5	✓ slight arc
5 60.00	Flat Anvil	Hot	1.5	180	9.5	35.1	25.0	10.1	11.1	10.7	✓ slight arc
6 59.47	Flat Anvil	Wet	1.5	173	9.3	34.8	27.0	7.8	10.8	10.4	✓ slight arc
7 58.91	Bitumen	Ambient	1.5	160	9.7	36.7	30.7	6.0	11.5	10.6	✓ slight arc
8 59.08	Concrete	Ambient	1.5	165	9.7	37.6	29.5	8.1	12.8	9.9	✓ arc
9 45.59	Car Pillar	Ambient	1.5	98	17.5	34.4	25.3	9.1	11.5	7.9	✓
10 60.58	Road Base Soil	Ambient	1.5	124	11.2	35.5	30.0	5.5	10.4	9.3	
11 96.33	Flat Anvil	Ambient	1.83	1st 206 2nd 286	 9.2 7.2	35.8	22.2	13.6	12.7	11.5	✓ arc
12 88.35	Flat Anvil	Cold	1.83	1st 219 2nd 295	 8.9 7.4	35.2	22.9	12.3	12.6	11.2	✓ arc
13 90.94	Flat Anvil	Hot	1.83	1st 206 2nd 285	 9.0 7.5	35.2	21.6	13.6	12.8	12.0	✓ arc
14 89.74	Flat Anvil	Wet	1.83	1st 216 2nd 285	 8.9 7.7	35.2	21.9	13.3	12.1	11.9	✓ arc
15 88.58	Bitumen	Ambient	1.83	184	9.7	37.5	29.3	8.2	11.3	10.6	✓ slight arc
16 84.28	Concrete	Ambient	1.83	203	9.3	35.4	25.5	9.9	12.0	11.2	✓ arc
17 76.38	Kerb Channel	Ambient	1.83	116	14.0	35.0	28.9	6.1	11.2	8.7	✓
18 89.56	Road Base Soil	Ambient	1.83	169	10.0	35.6	2.9.1	6.5	11.3	10.2	
*19 86.72	Flat Anvil	Ambient	1.83	1st 188 2nd 244	 9.0 7.7	35.6	23.1	12.5	10.9	10.7	✓ arc
*20 49.35	Flat Anvil	Ambient	1.5	159	9.9	34.4	25.5	8.9	10.4	10.2	✓ arc

- Reversed impacting surface

Mass of headform = 3402 g
Mass of headform + assembly = 5109 g

Table 2: Results for foam type B1.

Samples No./ Mass (g)	Impact Surface	Environ -ment	Drop Height (m)	Peak Deceler -ation (g force)	Average Time Duration (ms)	Thickness Before Crushing (mm)	Thickness At Base Of Crushing (mm)	Crushing Of Liner (mm)	Width Of Crushing At Long Axis (mm)	Width Of Crushing At Short Axis (mm)	Cracking (tick)
1 71.30	Flat Anvil	Ambient	0.5	103	9.2	34.4	32.4	2.0	7.5	6.7	
2 71.10	Flat Anvil	Ambient	1.0	162	8.7	34.3	29.1	5.2	9.0	8.3	✓ slight arc
3 65.30	Flat Anvil	Ambient	1.5	175	9.3	34.4	26.8	7.6	10.9	9.2	✓ slight arc
4 67.61	Flat Anvil	Cold	1.5	199	8.7	34.3	26.9	7.4	10.4	9.0	
5 66.75	Flat Anvil	Hot	1.5	166	9.0	34.2	27.2	7.0	10.4	9.4	
6 70.12	Flat Anvil	Wet	1.5	181	9.0	34.3	27.8	6.5	10.3	9.2	✓ slight arc
7 68.00	Bitumen	Ambient	1.5	179	8.9	34.3	27.2	7.1	11.0	9.5	✓ slight arc
8 66.00	Concrete	Ambient	1.5	176	8.9	34.3	26.6	7.7	10.6	9.1	✓ slight arc
9 65.13	Kerb Channel	Ambient	1.5	106	14.5	34.3	27.7	6.6	9.2	6.9	
10 68.00	Road Base Soil	Ambient	1.5	127	10.9	34.3	29.9	4.4	8.4	8.4	
11 96.68	Flat Anvil	Ambient	1.83	1st 203 2nd 274	8.7 7.4	35.1	22.7	12.4	11.9	11.9	✓ arc
12 94.00	Flat Anvil	Cold	1.83	1st 215 2nd 277	8.5 7.7	35.1	23.7	11.4	10.7	10.7	✓ arc
13 97.22	Flat Anvil	Hot	1.83	1st 193 2nd 219	9.0 8.5	35.1	22.4	12.7	12.3	11.3	✓ arc
14 98.14	Flat Anvil	Wet	1.83	1st 200 2nd 245	8.9 7.9	35.0	22.7	12.3	11.7	11.6	✓ arc
15 95.22	Bitumen	Ambient	1.83	199	9.0	35.1	26.1	9.0	11.1	10.0	✓ slight arc
16 95.69	Concrete	Ambient	1.83	199	9.0	35.2	26.7	8.5	10.9	10.2	✓ arc
17 95.28	Kerb Channel	Ambient	1.83	103	15.0	35.2	31.2	4.0	9.4	7.4	
18 96.43	Road Base Soil	Ambient	1.83	187	9.3	35.3	28.5	6.8	10.3	9.4	
*19 90.00	Flat Anvil	Ambient	1.83	1st 198 2nd 238	8.9 7.9	35.4	23.4	12.0	11.4	11.1	✓ arc
*20 65.00	Flat Anvil	Ambient	1.5	178	9.0	34.3	26.5	7.8	10.4	9.5	✓ slight arc

APPENDIX 2: RESULTS FROM TEST 2

Table 1: Results for foam type A2.

Samples No./ Mass (g)	Impact Surface	Environ -ment	Drop Height (m)	Peak Deceler -ation (g force)	Average Time Duration (ms)	Thickness Before Crushing (mm)	Thickness At Base Of Crushing (mm)	Crushing Of Liner (mm)	Width Of Crushing At Short Axis (mm)	Width Of Crushing At Long Axis (mm)	Cracking (tick)
1 58.60	Flat Anvil	Ambient	0.5	78	10.0	42.04 PE	37.44	4.60	8.1	8.0	
2 59.62	Flat Anvil	Ambient	1.0	108	10.7	42.08 PE	35.65	6.43	9.6	8.5	
3 59.83	Flat Anvil	Ambient	1.5	135	11.0	42.80 PE	35.54	7.26	10.5	9.7	
4 61.55	Flat Anvil	Cold	1.5	191	9.3	34.36	27.02	7.34	10.2	9.8	
5 61.59	Flat Anvil	Hot	1.5	174	9.3	35.43	27.21	8.22	10.3	10.1	
6 61.67	Flat Anvil	Wet	1.5	182	9.3	35.36	26.47	8.89	10.5	9.7	
7 61.91	Bitumen	Ambient	1.5	177	9.7	34.45	25.65	8.80	10.2	10.1	
8 61.98	Concrete	Ambient	1.5	185	9.3	36.48	27.96	8.52	10.3	9.6	
9 62.24	Kerb Channel	Ambient	1.5	96	13.0						✓right through
10 62.04	Road Base Soil	Ambient	1.5	128	11.0	34.34	28.20	6.14	10.3	9.0	✓opp side
11 132.11	Flat Anvil	Ambient	1.83	1st 205 2nd 268	9.3 8.3	36.60	25.07	11.53	11.8	10.8	✓ slight
12 132.46	Flat Anvil	Cold	1.83	1st 220 2nd 269	8.7 7.7	36.63	24.69	11.94	10.9	10.8	✓ slight
13 139.54	Flat Anvil	Hot	1.83	1st 201 2nd 253	9.3 8.0	36.63	23.83	12.80	12.1	10.7	✓ slight
14 121.47	Flat Anvil	Wet	1.83	1st 206 2nd 255	9.3 8.0	36.52	24.18	12.34	12.0	11.2	✓ slight
15 135.44	Bitumen	Ambient	1.83	205	9.3	36.81	27.72	9.09	11.0	9.9	
16 141.73	Concrete	Ambient	1.83	206	9.0	36.96	28.67	8.29	11.4	10.4	
17 136.76	Kerb Channel	Ambient	1.83	151	11.3	37.27	29.27	8.00	10.4	9.0	✓ severe
18 133.17	Road Base Soil	Ambient	1.83	175	10.0	36.84	29.53	7.31	10.5	9.4	
*19	Flat Anvil	Ambient No	1.83	1st 204	9.0						✓ slight

62.70		backing		2^{nd} 249	7.7	34.28	21.07	13.21	12.0	10.9	
*20 61.70	Flat Anvil	Hot	1.5	174	9.3	38.90 PE	28.16	10.74	10.6	10.0	✓ slight
*21 61.79	Flat Anvil	Wet	1.5	180	9.3	34.38	25.85	8.53	10.4	9.9	

* spare/repeats
PE = post expanded

Table 2: Results for foam type A2R (reversed).

Samples No./ Mass (g)	Impact Surface	Environ -ment	Drop Height (m)	Peak Deceler -ation (g force)	Average Time Duration (ms)	Thickness Before Crushing (mm)	Thickness At Base Of Crushing (mm)	Crushing Of Liner (mm)	Width Of Crushing At Long Axis (mm)	Width Of Crushing At Short Axis (mm)	Cracking (tick)
1 60.47	Flat Anvil	Ambient	0.5	92	9.3	37.58 PE	33.01	4.57	8.2	7.1	
2 60.51	Flat Anvil	Ambient	1.0	133	9.3	34.07	28.18	5.89	8.3	8.3	
3 60.73	Flat Anvil	Ambient	1.5	158	9.7	39.15 PE	31.67	7.48	9.2	9.0	
4 60.74	Flat Anvil	Cold	1.5	171	9.0	35.50	28.10	7.40	9.9	9.0	
5 62.87	Flat Anvil	Hot	1.5	153	9.3	34.26	26.45	7.81	9.3	9.0	✓
6 62.94	Flat Anvil	Wet	1.5	163	9.0	34.03	26.32	7.71	9.2	8.6	
7 62.79	Bitumen	Ambient	1.5	169	9.3	34.26	27.11	7.15	9.1	9.1	
8 62.79	Concrete	Ambient	1.5	174	9.7	34.46	27.12	7.34	9.6	9.1	
9 62.27 10 62.54	Kerb Channel Road Base Soil	Ambient Ambient	1.5 1.5	119 114	12.0 11.7	34.47	28.08	6.39	8.9	8.0	✓ ✓ opp. side
11 132.55	Flat Anvil	Ambient	1.83	1^{st} 184 2^{nd} 252	9.0 8.0	37.28	26.73	10.55	10.9	10.2	
12 131.52	Flat Anvil	Cold	1.83	1^{st} 208 2^{nd} 250	9.0 7.7	36.96	27.31	9.65	10.6	10.0	
13 129.67 14 131.35	Flat Anvil Flat Anvil	Hot Wet	1.83 1.83	1^{st} 189 2^{nd} 245 1^{st} 190 2^{nd} 236	9.3 8.0 9.3 8.3	36.90 36.68	25.47 25.90	11.43 10.78	11.4 10.9	10.1 10.1	
15 125.77	Bitumen	Ambient	1.83	191	9.0	36.61	29.50	7.11	9.4	9.2	
16 130.51	Concrete	Ambient	1.83	191	9.0	36.90	29.91	6.99	9.9	9.3	
17 136.16	Kerb Channel	Ambient	1.83	137	11.7	38.44 PE	29.27	9.17	9.0	7.5	
18 128.08	Road Base Soil	Ambient	1.83	176	9.7	37.79 PE	31.94	5.85	9.5	9.2	
*19 63.12	Flat Anvil	Ambient No backing	1.83	1^{st} 183 2^{nd} NT	9.0	34.55	25.54	9.01	9.8	9.1	✓

* spare/repeats
PE = post expanded

Table 3: Result for foam type B2

Samples No./ Mass (g)	Impact Surface	Environ -ment	Drop Height (m)	Peak Deceler -ation (g force)	Average Time Duration (ms)	Thickness Before Crushing (mm)	Thickness At Base Of Crushing (mm)	Crushing Of Liner (mm)	Width Of Crushing At Long Axis (mm)	Width Of Crushing At Short Axis (mm)	Cracking (tick)
1 70.06	Flat Anvil	Ambient	0.5	98	8.7	39.79 PE	36.30	3.49	7.4	7.4	
2 70.07	Flat Anvil	Ambient	1.0	124	9.7	40.79 PE	35.97	4.82	8.9	8.7	✓ slight arc
3 70.08	Flat Anvil	Ambient	1.5	168	9.0	38.16 PE	31.82	6.34	9.4	9.4	✓ slight arc
4 69.80	Flat Anvil	Cold	1.5	168	9.0	38.84 PE	32.15	6.69	9.8	9.3	✓ slight arc
5 69.88	Flat Anvil	Hot	1.5	161	9.3	38.83 PE	31.82	7.01	9.6	9.2	✓ slight arc
6 69.94	Flat Anvil	Wet	1.5	172	9.0	38.06 PE	30.67	7.39	9.3	9.1	✓ slight arc
7 70.23	Bitumen	Ambient	1.5	171	9.0	38.15 PE	31.20	6.95	9.4	9.3	✓ slight arc
8 70.23	Concrete	Ambient	1.5	168	9.3	38.90 PE	32.05	6.85	9.4	9.0	✓ slight arc
9 70.39	Kerb Channel	Ambient	1.5	104	12.0	PE			9.5	6.3	✓ through
10 70.39	Road Base Soil	Ambient	1.5	139	10.7	38.45 PE	34.34	4.11	8.8	8.5	
11 149.87	Flat Anvil	Ambient	1.83	1st 188 2nd 243	9.0 7.3	42.39 PE	29.93	12.46	11.0	10.2	✓ arc
12 137.36	Flat Anvil	Cold	1.83	1st 181 2nd 221	9.3 8.3	42.53 PE	29.68	12.85	11.1	10.2	✓ arc
13 141.76	Flat Anvil	Hot	1.83	1st 167 2nd 220	9.3 8.7	42.56 PE	29.93	12.63	11.4	10.4	✓ arc
14 142.02	Flat Anvil	Wet	1.83	1st 191 2nd 237	9.0 8.0	41.66 PE	28.77	12.89	11.0	10.2	✓ slight arc
15 141.78	Bitumen	Ambient	1.83	189	9.0	41.60 PE	33.32	8.28	10.0	9.4	✓ slight arc
16 144.44	Concrete	Ambient	1.83	174	9.0	43.45 PE	34.96	8.49	10.0	9.4	✓ arc
17 138.10	Kerb Channel	Ambient	1.83	144	10.3	41.95 PE	34.68	7.27	9.4	8.4	✓ slight arc
18 148.80	Road Base Soil	Ambient	1.83	159	9.7	43.49 PE	36.10	7.39	9.8	9.4	✓ arc
*19 70.50	Flat Anvil	Ambient No backing	1.83	1st 178 2nd 233	9.0 ?	38.88 PE	25.86	13.02	9.6 11.2	9.4 10.2	✓ arc

* spare/repeats
PE = post expanded

APPENDIX 3: RESULTS FROM TEST 3

Table 1: Results for foam type A3.

Samples No./ Mass (g)	Impact Surface	Environ -ment	Drop Height (m)	Peak Deceler -ation (g force)	Time Duration (ms)	Thickness Before Crushing (mm)	Thickness At Base Of Crushing (mm)	Crushing Of Liner (mm)	Width Of Crushing At Short Axis (mm)	Width Of Crushing At Long Axis (mm)	Cracking (tick)
1 63.10	Flat Anvil	Ambient	0.5	95.7	10.3	34.4	28.6	5.8	81	81	
2 63.65	Flat Anvil	Ambient	1.0	119.0	10.7	38.8	31.8	7.0	97	90	PE ✓ slight arc
3 63.85	Flat Anvil	Ambient	1.5	174.8	9.7	34.6	25.3	9.3	107	100	
4 63.87	Flat Anvil	Cold	1.5	183.7	9.0	34.4	26.0	8.4	107	104	
5 63.96	Flat Anvil	Hot	1.5	174.9	9.3	34.2	25.6	8.6	107	104	
6 64.04	Flat Anvil	Wet	1.5	180.2	9.0	34.5	25.2	9.3	105	103	
7 64.21	Bitumen	Ambient	1.5	178.9	9.3	34.3	25.5	8.8	107	107	
8 64.47	Concrete	Ambient	1.5	181.8	9.0	34.4	25.4	9.0	108	103	
9 64.50	Kerb Channel	Ambient	1.5	110.3	11.7	34.8	22.8	12.0	112	77	✓
10 64.54	Road Base Soil	Ambient	1.5	140.6	10.0	34.6	28.1	6.5	98	93	
11 64.55	Flat Anvil	Ambient	1.83	1st 204.4 2nd 264.6	9.0 8.0	37.5	20.8	16.7	120	113	✓ slight arc
12 64.70	Flat Anvil	Cold	1.83	1st 206.7 2nd 281.2	8.7 7.7	37.5	21.7	15.8	124	111	✓ slight arc
13 64.75	Flat Anvil	Hot	1.83	1st 203.0 2nd 265.6	9.0 8.3	37.6	21.2	16.4	128	110	✓ slight arc
14 64.85	Flat Anvil	Wet	1.83	1st 201.3 2nd 257.1	9.3 8.0	37.8	20.3	17.5	122	109	✓ slight arc
15 64.89	Bitumen	Ambient	1.83	204.4	9.3	37.6	24.8	12.8	108	108	✓ slight arc
16 65.38	Concrete	Ambient	1.83	203.6	9.0	37.6	24.7	12.9	113	104	✓ slight arc
17 65.39	Kerb Channel	Ambient	1.83	140.6	10.7	36.3	23.9	12.4	107	88	✓
18 65.50	Road Base Soil	Ambient	1.83	187.7	9.3	37.7	25.5	12.2	106	106	
*19											

*20											

Table 2: Results for foam type A4.

Samples No./ Mass (g)	Impact Surface	Environ -ment	Drop Height (m)	Peak Deceler -ation (g force)	Time Duration (ms)	Thickness Before Crushing (mm)	Thickness At Base Of Crushing (mm)	Crushing Of Liner (mm)	Width Of Crushing At Short Axis (mm)	Width Of Crushing At Long Axis (mm)	Cracking (tick)
1 62.45	Flat Anvil	Ambient	0.5	94.2	10.7	34.5	28.7	5.8	87	80	
2 62.53	Flat Anvil	Ambient	1.0	142.6	10.0	34.6	26.7	7.9	101	94	
3 62.58	Flat Anvil	Ambient	1.5	177.6	9.7	34.4	25.5	8.9	102	102	
4 62.68	Flat Anvil	Cold	1.5	183.6	9.0	34.5	25.7	8.8	102	101	
5 62.73	Flat Anvil	Hot	1.5	173.2	9.3	34.4	25.7	8.7	106	102	
6 62.75	Flat Anvil	Wet	1.5	179.4	9.0	34.3	25.4	8.9	104	104	
7 62.90	Bitumen	Ambient	1.5	179.1	9.3	34.3	25.7	8.6	103	106	
8 63.11	Concrete	Ambient	1.5	182.2	9.0	34.4	25.4	9.0	106	106	
9 63.14	Kerb Channel	Ambient	1.5	110.5	13.3	34.4	22.6	11.8	110	76	✓
10 63.16	Road Base Soil	Ambient	1.5	150.8	10.0	34.6	27.9	6.7	100	100	
11 63.27	Flat Anvil	Ambient	1.83	1^{st} 201.7 2^{nd} 264.5	9.0 8.3	37.9	21.5	16.4	124	111	✓ arc
12 63.39	Flat Anvil	Cold	1.83	1^{st} 215.3 2^{nd} 279.7	9.0 8.0	37.6	21.9	15.7	122	114	✓ arc
13 63.41	Flat Anvil	Hot	1.83	1^{st} 199.8 2^{nd} 238.3	9.3 8.3	37.4	20.8	16.6	129	114	✓ arc
14 63.46	Flat Anvil	Wet	1.83	1^{st} 200.6 2^{nd} 258.7	9.0 8.0	37.5	20.8	16.7	122	115	✓ arc
15 63.48	Bitumen	Ambient	1.83	203.7	9.3	37.3	24.9	12.4	111	111	✓ slight arc
16 63.64	Concrete	Ambient	1.83	199.6	9.0	37.4	24.7	12.7	115	107	
17 63.71	Kerb Channel	Ambient	1.83	168.5	10.0	38.2	25.2	13.0	108	94	✓
18 63.89	Road Base Soil	Ambient	1.83	187.0	9.3	37.7	25.7	12.0	108	103	
*19											
*20											

Table 3: Results for foam type B3.

Samples No./ Mass (g)	Impact Surface	Environ -ment	Drop Height (m)	Peak Deceler -ation (g force)	Time Duration (ms)	Thickness Before Crushing (mm)	Thickness At Base Of Crushing (mm)	Crushing Of Liner (mm)	Width Of Crushing At Short Axis (mm)	Width Of Crushing At Long Axis (mm)	Cracking (tick)
1 68.75	Flat Anvil	Ambient	0.5	103.7	9.7	34.6	29.4	5.2	77	70	
2 69.08	Flat Anvil	Ambient	1.0	114.6	10.0	38.8	32.8	6.0	89	86	PE ✓ slight arc
3 69.42	Flat Anvil	Ambient	1.5	161.0	9.7	37.0	29.0	8.0	98	93	Slight PE ✓ slight arc
4 69.84	Flat Anvil	Cold	1.5	165.7	9.0	37.4	30.2	7.2	95	92	Slight PE ✓ slight arc
5 70.15	Flat Anvil	Hot	1.5	151.7	9.3	36.9	30.3	6.6	95	95	PE ✓ slight arc
6 70.34	Flat Anvil	Wet	1.5	156.0	9.0	37.6	30.4	7.2	94	94	Slight PE ✓ slight arc
7 70.49	Bitumen	Ambient	1.5	177.3	9.0	35.0	27.0	8.0	98	93	
8 70.50	Concrete	Ambient	1.5	165.9	8.7	35.9	28.9	7.0	94	94	Slight PE ✓ slight arc
9 70.62	Kerb Channel	Ambient	1.5	114.9	10.3	34.4	33.0	11.4	108	59	✓
10 70.68	Road Base Soil	Ambient	1.5	154.8	9.3	36.0	29.7	6.3	94	89	
11 157.65	Flat Anvil	Ambient	1.83	1st 202.3 2nd 264.6	8.7 7.7	38.0	22.0	16.0	115	106	✓ arc
12 122.88	Flat Anvil	Cold	1.83	1st 203.0 2nd 266.1	8.7 7.7	38.3	24.0	14.3	114	102	✓ arc
13 125.52	Flat Anvil	Hot	1.83	1st 163.0 2nd 216.4	9.3 8.7	39.3	26.0	13.3	112	104	Slight PE ✓ arc
14 123.60	Flat Anvil	Wet	1.83	1st 169.2 2nd 224.5	9.3 8.3	40.0	24.7	15.3	110	103	✓ severe arc
15 119.96	Bitumen	Ambient	1.83	184.6	9.3	39.0	27.8	11.2	96	92	Slight PE ✓ slight arc
16 121.65	Concrete	Ambient	1.83	182.4	9.3	37.7	28.2	9.5	96	95	Slight PE ✓ arc
17 118.88	Kerb Channel	Ambient	1.83	121.7	13.3	38.8	28.1	10.7	96	83	Slight PE ✓ severe arc

18 124.45	Road Base Soil	Ambient	1.83	169.0	9.3	39.0	29.4	9.6	96	88	Slight PE ✓ arc
*19											
*20											

PE = post expanded

APPENDIX 4: RESULTS FROM SUPPLEMENTARY TEST.

Table 1: Results for foam type A2(M).

Samples No../ Mass (g)	Impact Surface	Environ -ment	Drop Height (m)	Peak Deceler -ation (g force)	Time Duration (ms)	Thickness Before Crushing (mm)	Thickness At Base Of Crushing (mm)	Crushing Of Liner (mm)	Width Of Crushing At Short Axis (mm)	Width Of Crushing At Long Axis (mm)	Cracking (tick)
1 57.89	Flat Anvil	Ambient	0.5	105.1	10.3	25.5	19.4	6.1	80	80	
2 58.11	Flat Anvil	Ambient	1.0	156.4	9.3	24.5	16.6	7.9	99	93	
3 58.13	Flat Anvil	Ambient	1.5	196.3	9.0	25.3	15.7	9.6	108	100	
4 94.05	Flat Anvil	Ambient	1.83	1st 216.4 2nd 322.5	9.0 7.7	27.2	11.7	15.5	123	105	✓ arc

Table 2: Results for foam type B2(M).

Samples No../ Mass (g)	Impact Surface	Environ -ment	Drop Height (m)	Peak Deceler -ation (g force)	Time Duration (ms)	Thickness Before Crushing (mm)	Thickness At Base Of Crushing (mm)	Crushing Of Liner (mm)	Width Of Crushing At Short Axis (mm)	Width Of Crushing At Long Axis (mm)	Cracking (tick)
1 69.71	Flat Anvil	Ambient	0.5	99.3	9.7	27.1	21.8	5.3	73	69	
2 69.81	Flat Anvil	Ambient	1.0	143.9	9.0	27.2	20.1	7.1	89	82	
3 69.91	Flat Anvil	Ambient	1.5	177.4	9.0	27.2	18.4	8.8	97	91	
4 98.40	Flat Anvil	Ambient	1.83	1st 200.3 2nd 272.0	9.0 7.7	28.2	13.7	14.5	113	99	✓ arc

APPENDIX 5: PERCENTAGE INCREASE/DECREASE IN CRUSHING

Table 1: Percentage increase/decrease in crushing for test 1 and test 3.

Samples No.	Impact Surface	Environ -ment	Drop Height (m)	PERCENTAGE CRUSHING Test 1 A1 (70/30 kg/m^3)	B1 (70 kg/m^3)	A1 % Increase/ decrease	Test 3 A3 (75/30 kg/m^3)	A4 (75/25 kg/m^3)	B3 (75 kg/m^3)	A3 % Increase/ decrease	A4% Increase / decrease
1	Flat Anvil	Ambient	0.5	16.2	5.8	+ 10.4	16.9	16.8	15.0	+ 1.9	+ 1.8
2	Flat Anvil	Ambient	1.0	21.4	15.2	+ 6.2	18.0	22.8	15.5	+ 2.5	+ 7.3
3	Flat Anvil	Ambient	1.5	24.3	22.1	+ 2.2	26.9	25.9	21.6	+ 5.3	+ 4.3
4	Flat Anvil	Cold	1.5	25.6	21.6	+ 4.0	24.4	25.5	19.3	+ 5.1	+ 6.2
5	Flat Anvil	Hot	1.5	28.8	20.5	+ 8.3	25.1	25.3	17.9	+ 7.2	+ 7.4
6	Flat Anvil	Wet	1.5	22.4	19.0	+ 3.4	27.0	25.9	19.1	+ 7.9	+ 6.8
7	Bitumen	Ambient	1.5	16.3	20.7	- 4.4	25.7	25.1	22.9	+ 2.8	+ 2.2
8	Concrete	Ambient	1.5	21.5	22.4	- 0.9	26.2	26.2	19.5	+ 6.7	+ 6.7
9	Kerb Channel	Ambient	1.5	26.5	19.2	+ 7.3	34.5	34.3	33.1	+ 1.4	+ 1.2
10	Road Base Soil	Ambient	1.5	15.5	12.8	+ 2.7	18.8	19.4	17.5	+ 1.3	+ 1.9
11	Flat Anvil	Ambient	1.83	38.0	35.3	+ 2.7	44.5	43.3	42.1	+ 2.4	+ 1.2
12	Flat Anvil	Cold	1.83	34.9	32.5	+ 2.4	42.1	41.8	37.3	+ 4.8	+ 4.5
13	Flat Anvil	Hot	1.83	38.6	36.2	+ 2.4	43.6	44.4	33.8	+ 9.8	+ 10.6
14	Flat Anvil	Wet	1.83	37.8	35.1	+ 2.7	46.3	44.5	38.3	+ 8.0	+ 6.2
15	Bitumen	Ambient	1.83	21.9	25.6	- 3.7	34.0	33.2	28.7	+ 5.3	+ 4.5
16	Concrete	Ambient	1.83	28.0	24.1	+ 3.9	34.3	33.9	25.2	+ 9.1	+ 8.7
17	Kerb Channel	Ambient	1.83	17.4	11.4	+ 6.0	34.2	34.0	27.6	+ 6.6	+ 6.4
18	Road Base Soil	Ambient	1.83	18.2	19.3	- 1.1	32.4	31.8	24.6	+ 7.8	+ 7.2
*19	Flat Anvil	Ambient	1.83	35.1	33.9	+ 1.2					
*20	Flat Anvil	Ambient	1.5	25.9	22.7	+ 3.2					

Table 2: Percentage increase/decrease in crushing for test 2.

Samples No.	Impact Surface	Environ -ment	Drop Height (m)	PERCENTAGE CRUSHING Test 2				
				A2 (75/30 kg/m^3)	A2R (75/30 kg/m^3)	B2 (75 kg/m^3)	A2 % Increase/ decrease	A2R % Increase/ decrease
1 2	Flat Anvil Flat Anvil	Ambient Ambient	0.5 1.0	10.9 15.3	12.2 17.3	8.8 11.8	+ 2.1 + 3.5	+ 3.4 + 5.5
3	Flat Anvil	Ambient	1.5	17.0	19.1	16.6	+ 0.4	+ 2.5
4	Flat Anvil	Cold	1.5	21.4	20.8	17.2	+ 4.2	+ 3.6
5	Flat Anvil	Hot	1.5	23.2	22.8	18.0	+ 5.2	+ 4.8
6	Flat Anvil	Wet	1.5	25.1	22.7	19.4	+ 5.7	+ 3.3
7	Bitumen	Ambient	1.5	25.5	20.9	18.2	+ 7.3	+ 2.7
8	Concrete	Ambient	1.5	23.4	21.3	17.6	+ 5.8	+ 3.7
9	Kerb Channel	Ambient	1.5					
10	Road Base Soil	Ambient	1.5	17.9	18.5	10.7	+ 7.2	+ 7.8
11	Flat Anvil	Ambient	1.83	31.5	28.3	29.4	+ 2.1	- 1.1
12	Flat Anvil	Cold	1.83	32.6	26.1	30.2	+ 2.4	- 4.1
13	Flat Anvil	Hot	1.83	34.9	30.9	29.7	+ 5.2	+ 1.2
14	Flat Anvil	Wet	1.83	33.8	29.4	30.9	+ 2.9	- 1.5
15	Bitumen	Ambient	1.83	24.7	19.4	19.4	+ 4.8	- 0.4
16	Concrete	Ambient	1.83	22.4	18.9	19.5	+ 2.9	- 0.6
17	Kerb Channel	Ambient	1.83	21.5	23.9	17.3	+ 4.2	+ 6.6
18	Road Base Soil	Ambient	1.83	19.8	15.5	17.0	+ 2.8	- 1.5
*19	Flat Anvil	Ambient/ No backing	1.83	38.5	26.1	33.5	+ 5.0	- 7.4
*20	Spare/ repeat							

Table 3: Average percentage increase in crushing for foam samples tested.

Drop Height (m)	A1 (%)	A2 (%)	A2R (%)	A3 (%)	A4 (%)
0.5 to 1.5	+3.9	+4.6	+4.1	+4.2	+4.6
1.83	+1.9	+3.4	-1.4	+6.7	+6.2

Table 4: Maximum percentage increase/decrease in crushing for foam samples tested.

Drop Height (m)	A1 (%)	A2 (%)	A2R (%)	A3 (%)	A4 (%)
0.5 to 1.5	+10.4	+7.3	+5.5	+7.9	+7.4
1.83	+6.0	+5.2	+6.6	+9.8	+10.6