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Material Tests for Module Type Crash Cushion

모듈타입 충격흡수장치를 위한 재료실험

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요 지

형상이 일정하지 않은 구조에 충돌하는 차량의 탑승자 안전을 확보하기 위해서 그 구조물의 앞에 공간이 허용하는 한도의 깊이만큼 충격을 흡수하는 재료로 만든 모듈을 쌓아두는 방법을 생각할 수 있다. 충격흡수모듈로 사용되기 위해서는 재료가 충분한 에너지 흡수능력을 가져야 하고 동시에 탑승자의 안전을 확보할 수 있어야 한다. 본 논문에서는 에너지 흡수능력과 더불어 탑승자의 안전을 보장하기 위하여 충격흡수재료가 가져야 할 조건을 설명하고 Quard-Guard 시스템 모듈, 샌드백, 재활용 타이어, 지오컨테이너, 지오셀 그리고 EPS 블록에 대한 정적압축실험을 실시하여 그 결과를 분석하였다. 이로부터 30kg/m³의 밀도를 갖는 EPS 블록이 쿠션모듈로 사용되기 적합한 재료임을 보였다. 한편 시속 35.6km/h까지의 충돌조건으로 Drop Test를 실시하여 EPS 블록의 정적특성과 동적특성간 큰 차이가 없음을 보여 주었으며 쿠션모듈로서의 성질을 개선시키기 위한 방안으로 EPS 블록에 공극을 두는 방안을 제안하고 공극이 있는 EPS블록에 대하여 Drop Test를 실시하여 EPS 블록을 이용한 충격흡수시설의 설계에 필요한 재료적 특성치를 제시하였다.

핵심용어 : 비정형구조, 충돌, 쿠션, 모듈, 정적실험, 낙하실험

Abstract

One way to shield an atypical structure to secure the occupant safety of an impact vehicle is to stack energy absorbing material modules arround the structure. To be applicable to a cushion module, material must have enough energy absorbing capabilities while satisfying the safety requirements of the vehicle occupant. Static compression test of the potential materials gives a good indication which material is good for a stacking module. This paper presents the mechanical properties that a cushion material must have to satisfy the safety requirements. Static tests are performed for Quard-Guard system module, sand bag, recycled tires, Geo-Container, Geo-Cell and Expanded Polystyren (EPS) Blocks. Static test results are discussed and EPS block of 30kg/m³ density showed good potential for a cushion module. To check the dynamic effect of EPS block, drop tests have been made up to 35.6km/h impact speed. Drop test results are compared with static test results and no appreciable difference was found. To improve the EPS module property, making holes to the block is suggested and drop test are performed for the modified blocks. From the drop test results, design values are suggested.

Keywords : atypical structure, impact, cushion, module, static test, drop test

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1. Introduction

Crash Cushion is a device designed to safely stop a vehicle within a relatively short distance. Most of the crash cushions being used today are for the end of the rigid safety shape barrier or for gore areas. There are many different shape of structures that are exposed to traffic posing potential danger to the traffics. Overpass piers of different size and section geometry that are located at intersections, or along the medians of the downtown streets are few of the examples of atypical structures need to be shielded by crash cushions. The variety in geometric shapes and dimensions of the structures to be shielded and varying spaces around the structures have been the major obstacles to the development of a crash cushion for this environment, leaving many of those dangerous spots unshielded.

This paper deals with finding potential cushion materials for those atypical structures. Fig.1 shows module type crash cushion staked around an atypical structure. Forming the crash cushion by stacking modules will have advantages in that it can shield structures of any configurations, and is easy to form and replace locally after being crashed. Also, it does not have a space limitation if engineer can tailor the performance of the crash cushion as per the field conditions. To shield the atypical structures, stacking modules of proper materials blocks in the limit of available space is an option.

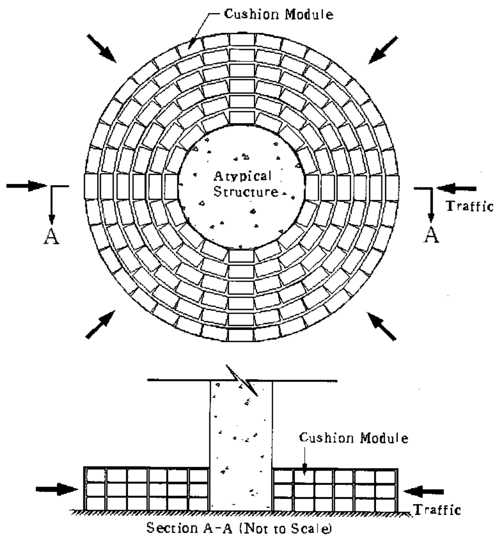

Fig.1 Module Type Crash Cushion

2. Equation for Material Selection

For an effective design of crash cushion, understanding vehicle motion during impact and mechanical properties of the cushion is essential. KO et al.(2005) studied structural parameters affecting the occupant safety using 2-DOF system model describing vehicle crash against cushion . From the study two design equations have been developed, which can be applicable to the design of module type crash cushion for 1.3ton-60km/h and 1.3ton-80km/h impact.

For the efficient study, two degree of freedom mass-spring model was developed to describe the impact vehicle and crash cushion. Then, it was used to identify the structural factors of crash cushion affecting the safety indices such as Occupant Impact Velocity(OIV) and Ridedown Acceleration(RA). These two safety indices and maximum crush distance have been shown as contours with major structural parameters, yield load F_y and post-yield stiffness k_t as its horizontal and vertical axis respectively. This graph helps in selecting structural design parameters satisfying the safety requirements. From the study, following conclusions were made;

a) Influential structural parameter of crash cushion on occupant safety represented by OIV and RA, are yield load F_y and post-yield stiffness k_t. Influence of initial stiffness on the occupant safety is insignificant.

b) 1.3ton vehicle impacting against a cushion was modeled by 2-DOF system. The model was used for extensive parametric study and the resulting accelerations were analyzed to produce safety indices and maximum crush distance. From the results, following two material selection equations were developed according to the design conditions (RA < 20g and OIV < 12m/sec) which Korean Design Guide specifies (MOTC, 1998).

$$k_t / 110 + F_y / 140 < 1 \quad \text{for 1.3ton-60km/h} \qquad (1)$$

$$k_t / 60 + F_y / 140 < 1 \quad \text{for 1.3ton-80km/h} \qquad (2)$$

Required crush distances for the two impact conditions were found to be 140cm for 1.3ton-60km/h impact and 275cm for 1.3ton-80km/h impact.

3. Statics Test of Materials

Potential materials that can be stacked around the atypical structures include were Sand Bag, Recycled Tire, Geo-Container, Geo-Cell, cartridge of Quard-Guard system and EPS(Expanded Polystyrene) blocks. Those material were compression tested and the resulting force-deformation relationships were investigated. Loading speed was 25mm/min and loading stopped at the 40% crush of the original dimension.

3.1 Quard Guard System

Fig.2(a) is the test setup for Quard Guard System and, Fig.2(b) is the test result of the type-1 and type-2 cartridges of Quard Guard system (Energy Absorption System. INC. 2007). In the test, the cartridge showed plastic deformation at 34kN loading (60mm deformation) with slight stiffness of 155.9 kN/mm. This kind of yield at small deformation and relatively high yield load, and small post-yield stiffness are the ideal characteristics of crush cushion. The cushion material selection factor calculated based on the Eq.1 was 1.68. Even the factor of greater than 1, considering approximating nature of the equation and the satisfactory crash test result of the Quard Guard system, the value greater than 1 is not to be dismissed.

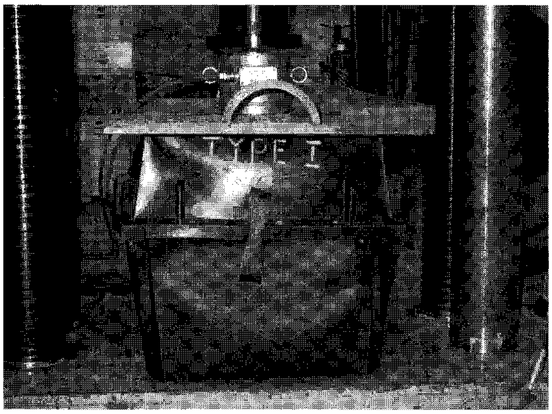

Fig. 2(a) Test Setup (Quard Guard System)

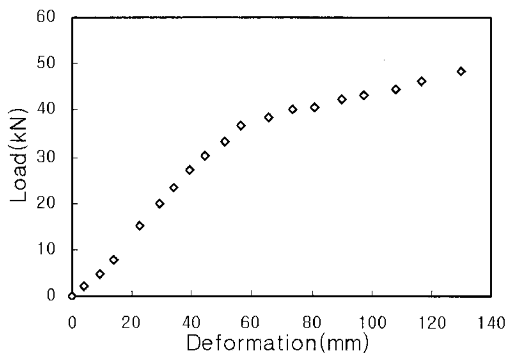

Fig. 2(b) Load-Deformention (Quard Guard System)

3.2 Sand Bag

Sand Bag is used for PE cushion system and is one of the cheapest material. For the compressive test, sand was compacted to the 80% of the maximum dry density in a bag. In the test sand bags were layered from 1 up to 5 layers. Test results are presented in Fig.3(b). Very early bottoming appeared in the 1 layered sand bag test and, as the layer increased, the flow of force-deformation curve was to be seen after the breakage of the bag. As the number of layers increased, the flow started at the earlier stage of deformation with lower force level. Test result shows that the energy absorbing capabilities of layered sand bag is quite low and is not applicable to resistive type crash cushion.

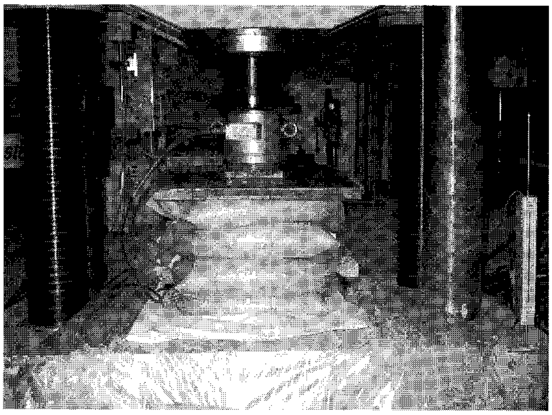

Fig. 3(a) Test Setup (Sand Bag)

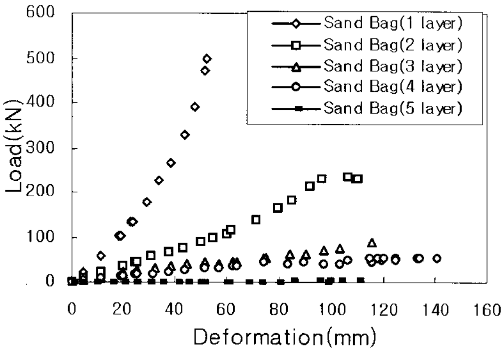

Fig. 3(b) Load-Deformention (Sand Bag)

3.3 Recycled Tire

Five tires were stacked in horizontal and vertical layer. As can be seen from the result in Fig.4(b) only small amount of energy can be absorbed by layered tires in horizontal direction, even it is better than the case layered in vertical direction. The force-deformation curves show strong linear elastic relations up to deformation of 18cm, which compares quite differently from other materials. Characteristics as a cushion material. Contrary to what one perhaps expected, those are the disadvantageous.

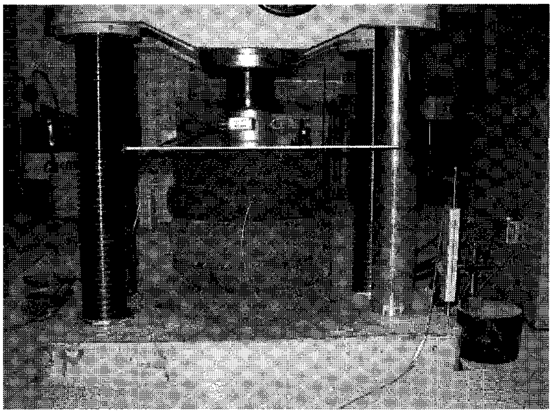

Fig. 4(a) Test Setup (Recycle Tire)

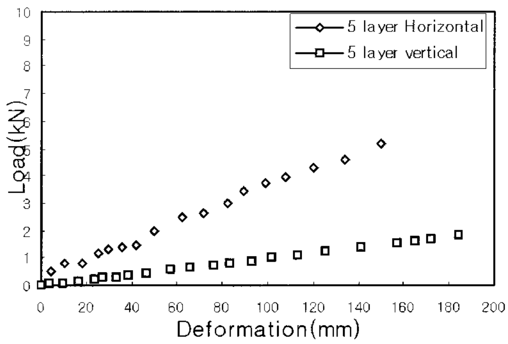

Fig. 4(b) Load-Deformention (Recycle Tire)

3.4 Geo-Container

It is used for PE Cushion system and is similar to sand bag but has larger tensional strength. For the compression test, sand was compacted to the 80% of the maximum dry density in a bag. Fig.5(b) is the test result. In the test, Geo-Containers were layered from 1 up to 5 layers. In the test for 1 layer geo-container, early bottoming appears and as the layer increases, result shows similar trend to that of sand bag. However, because of their larger tensile strength, the deformation at the point of first yield increases. The flow starts after the breakage of the bag. As the number of layers increases, the yield point appears at the early stage of deformation and at lower force level. This makes Geo-container stacking around the atypical structures unpredictable.

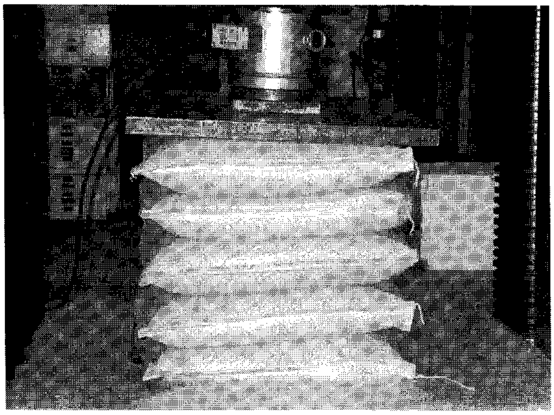

Fig. 5(a) Test Setup (Geo-Container)

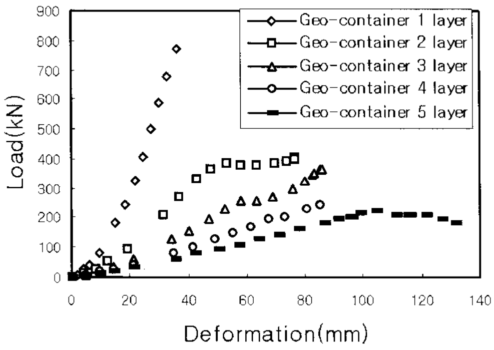

Fig. 5(b) Load-Deformention (Geo-Container)

3.5 Geo-Cell

Geo-Cell consists of multi-cells, which enhances load distribution and lateral confinements compared to the sand bag or Geo-Container. Fig.6 shows the compression test result of one and two layered Geo-Cell specimen. As can be seen from the result, Geo-Cell do not show any plastic flow which is not a desirable characteristics as a Crash Cushion.

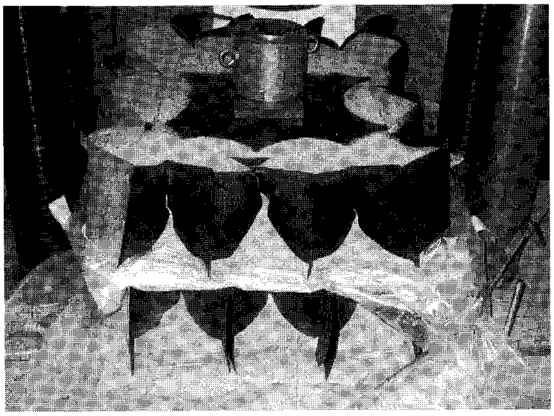

Fig. 6(a) Test Setup (Geo-Cell)

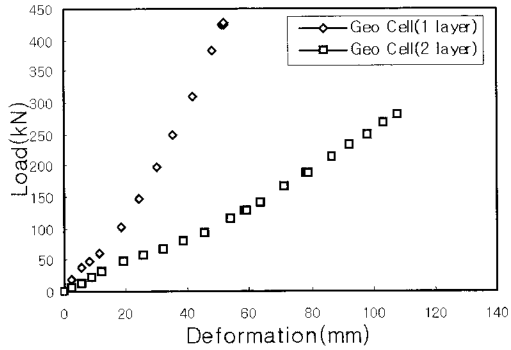

Fig. 6(b) Load-Deformention (Geo-Cell)

3.6 Expanded Polystyrene(EPS)

EPS blocks of different density of 15kg/m^3(denoted as D15), 20kg/m^3(denoted as D20) and 30kg/m^3(denoted as D30) were compression tested as in Fig.7(a). The dimension of one block was 450mm×450mm×400mm. Tests were made for one layer and two layers with different density combinations. Fig.7(b) shows the force-deformation relations and Table.1 summarizes it. From the figure it can be seen that EPS blocks have very small elastic deformation and yield point is pronouncing. But yield point is very low for the EPS block of density 15kg/m^3(D15). For the case, bottoming can be seen at deformation of 220mm. D30 specimen shows yield load of 28.7kN but very high post-yield stiffness of 277.47 kN/mm, which is lowered to 105.98 kN/mm when D30 blocks are stacked. Generally speaking, EPS blocks when they are stacked shows good potential as the crash cushion materials showing the material selection factor of Eq.1 close to 1. The closeness to factor 1 is possible when the yield load is about 140-160kN, and post yield stiffness is as little as possible. This means force-deformation curve similar to rigid perfectly plastic one has good potential to be used as crash cushion materials. In the sense, Stacked EPS block has good mechanical properties to be used as crash cushion materials for shielding atypical structures. Among various density block combinations the stacked D30 blocks show the best potential for crash cushion design. It gave high energy absorbing potentials while maintaining relatively low selection factor of Eq.1.

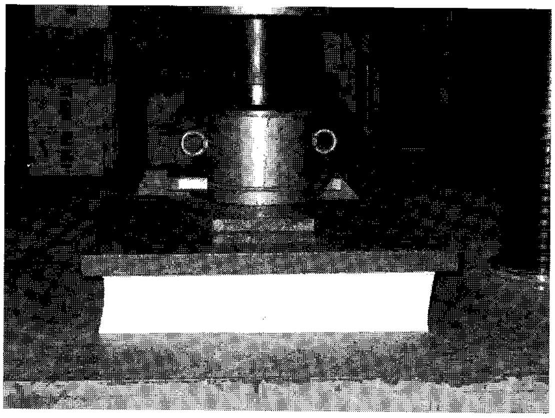

Fig. 7(a) Test Setup (EPS)

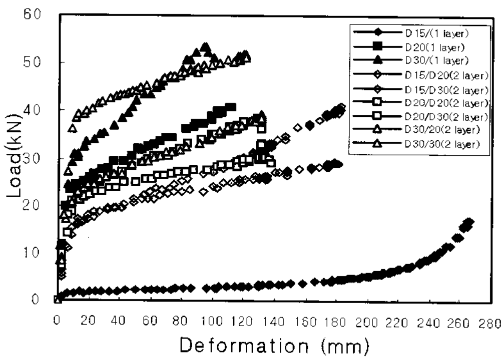

Fig. 7(b) Load-Deformention (EPS)

Table .1 Cushion Materials Selection Factor of EPS Blocks

Test Item	k_t	P_y	Selection Factor (Eq.1)
D15 (1 layer)	25.24	1.52	0.24
D20 (1 layer)	175.5	22.05	1.73
D30 (1 layer)	277.47	28.665	2.70
D15/D20 (2 layer)	77.49	16.17	0.81
D15/D30 (2 layer)	142.5	16.60	1.39
D20/D20 (2 layer)	67.67	21.56	0.75
D20/D30 (2 layer)	132.0	23.03	1.34
D30/D20 (2 layer)	132.0	23.03	1.34
D30/D30 (2 layer)	105.98	39.94	1.21

4. Drop Test of EPS Block

To see the influence of impact velocity on the force-deformation relation, drop test was performed for the EPS blocks. The test drops the mass of 300kg from the lifted position. Piezo type accelerometer 352B32 was mounted on the top of the mass (Piezotronics Vibration Division, 2002). Accelerations are measured and double integrated for crush distance, with initial velocity of $v_o = \sqrt{2gh}$ and initial deformation of zero, from which force-deformation relations could be found. Test results are in Fig.10. In the figures, test specimens are denoted as DxxAyHz or DxxSyHz, where, Dxx means density of specimen is xxkg/m^3, Ay represents 'y' numbers of holes, Sy represents 'y' numbers of holes filled with dry sand, and Hz means drop height is 'z' m.

4.1 D20 EPS Blocks

EPS block(450×450×300mm) of density 20kg/m³ was hit by the mass from 1m to 5m height. The test results are in the Fig.8(a), 8(b), 8(c). Acceleration was measured and velocity, deformation were calculated from the acceleration by successive integration and force-deformation relations were sought. Time history of acceleration is shown in Fig.8(a), force-deformation in Fig.8(b) and energy-deformation in Fig.8(c). Free fall from 5m height is equivalent to 35.6km/h impact. This impact resulted maximum acceleration of 71g. Bottoming of the block is clearly visible in Fig.8(b). It shows the bottoming of the EPS block for the 3, 4, 5m free fall started from 20cm deformation. It is of interest to note that the envelope of force-deformation curve of different impacts are the same, meaning no appreciable velocity sensitivity in the material property are expected. Fig.8(c) shows that 450×450×300 EPS block of density 20kg/m³ can absorb impact energy of 6.07kJ before bottoming.

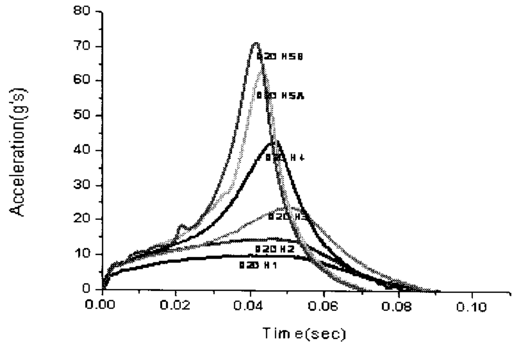

Fig. 8(a) Acceleration (D20 EPS Block)
(H=1, 2, 3, 4, 5m Free Fall)

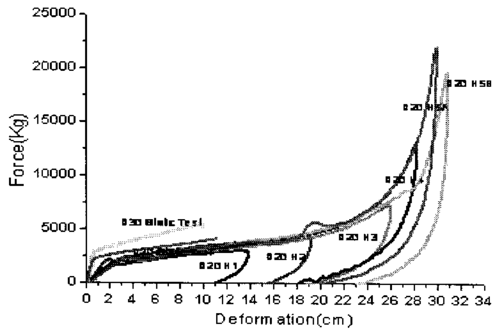

Fig. 8(b) Force-Deformation (D20 EPS Block)
(H=1, 2, 3, 4, 5m Free Fall)

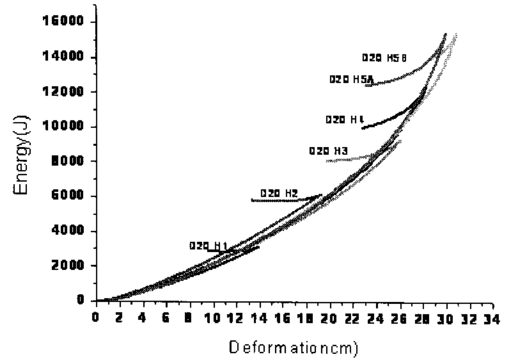

Fig. 8(c) Energy-Deformation(D20 EPS Block)
(H=1, 2, 3, 4, 5m Free Fall)

4.2 D30 EPS Blocks

EPS block(450×450×300mm) of density 30kg/m³ was hit by 310kg mass from 1m to 5m height. Acceleration was measured and velocity, deformation was calculated from the acceleration by successive integration and force-deformation relations were sought. Time history of acceleration is shown in Fig.6(a), force-deformation in Fig.9(b) and energy-deformation in Fig.6(c). Free fall from 5m height is equivalent to 35.6km/h impact. This impact resulted maximum acceleration of 33.7g. This is very low value compared to the maximum acceleration measured for the 20kg/m³ EPS block, which means that the 30kg/m³ EPS block has not reached to the perfect bottoming as the 20kg/m³ block by the 35.6km/h impact. Bottoming of the block is seen to start from around 20cm deformation by the 4m free fall impact. It shows that the bottoming of the EPS block for the 3, 4, 5m free fall starts from 20cm deformation. It is of interest to note that the envelope of force-deformation curve of different impacts are the same, meaning no appreciable velocity sensitivity in the material property are expected. Fig.6(c) shows that 450×450×300 EPS block of density 30kg/m^3 can absorb impact energy of 10.0kJ before bottoming.

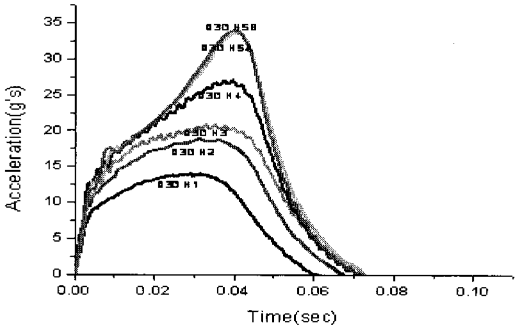

Fig. 9(a) Acceleration (D30 EPS Block)
(H=1, 2, 3, 4, 5m Free Fall)

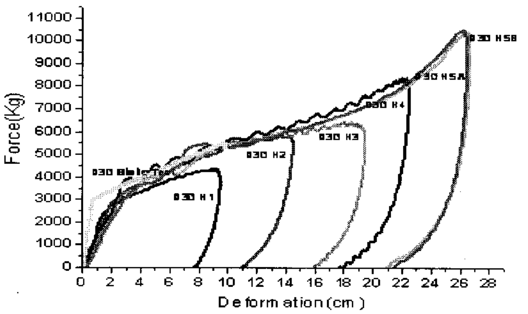

Fig. 9(b) Force-Deformation (D30 EPS Block)
(H=1, 2, 3, 4, 5m Free Fall)

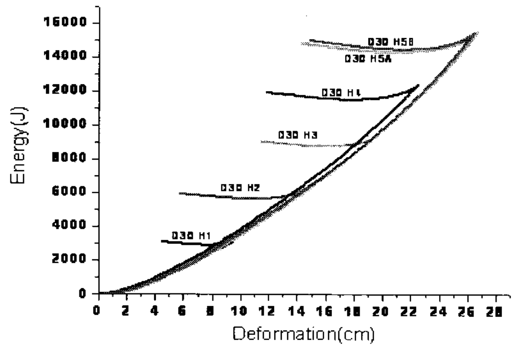

Fig. 9(c) Energy-Deformation(D30 EPS Block)
(H=1, 2, 3, 4, 5m Free Fall)

4.3 Modified D30 EPS Block

After the drop test, it was decided to provide some void space in the EPS block so as to facilitate the crushing when the blocks are stacked and confined laterally. Providing voids to a EPS solid block was believed to reduce the post yield stiffness k_t and increase the crushable distance. Also, it could reduce the possibility of rebound. Diameter of the void hole was 5cm and numbers of the holes were 1, 4 and 9. Holes were left void or filled with dry sand.

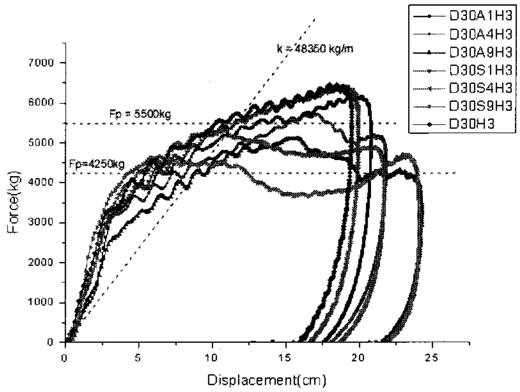

Fig. 10 Force-Displacement
(Modified 30kg/m^3 EPS Block)

The result shows that as the number of the holes increases, post-yield stiffness decreases. Filling the void by sand increases the first yield load, but crushes the specimen earlier than the case of specimen with the holes left void. This is probably due to the increasing lateral pressure of the sand that is compressed vertically. From this test, it can be seen that the void in the block decreases the post-yield stiffness and increases the crush distance. It is desirable to use the D30 block with 9 5cm-dia holes for the crash cushion design, where crush force F_p can be regarded as 4500kg. Also, crush distance of the EPS block with the 9 hole can be taken as 70-80% of the original dimension.

5. Conclusion

To shield the atypical structures which are exposed to traffics, stacking cushion modules at the face of the structures is a solution. To be applicable to a cushion module, material must have enough energy absorbing capabilities while satisfying the safety requirements of the vehicle occupant. Influential parameter of cushion material on occupant safety represented by OIV and RA, are yield force F_y and post-yield stiffness k_t. The selecting factor $k_t/110 + F_y/140$ must be less than 1 to satisfy the safety requirement of the Korean Design Guide for 1.3ton-60km/h impact.

Static compressive tests are performed for Quard-Guard system module, sand bag, recycled tires, Geo-Container, Geo-Cell and Expanded Polystyren (EPS) Blocks. Based on the selecting factor, EPS of 30kg/m³ showed good potential as a cushion module.

To check the dynamic effect of EPS block drop tests have been made up to 35.6km/h impact speed. Drop test results are compared with static test results and no appreciable difference are found. In the low speed impact, material property of EPS block, especially force-deformation relation, is not rate-sensitive. EPS block (450×450×300mm) of density 20kg/m³ can absorb 6*KJ* impact energy before bottoming at 20cm deformation, while 30kg/m³ block can absorb 10*KJ* at the same deformation.

To improve the module property of the 30Kg/m³ EPS block, making void holes to the block is suggested and drop test are performed for the modified blocks with 9cm-dia holes. Crush force, F_y was found to be 4,500~5,000kg. Crush distance of the EPS block with the 9 hole was regarded as 70~80% of the original dimension.

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