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DEFORMATION ANALYSIS OF RUBBER BLOCKS UNDER LARGE COMPRESSIVE STRAIN

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ABSTRACT

Rubbers are relatively soft materials that undergo large deformation upon loading. The deformation behavior of the elastomeric materials under large strain is still far from being understood today. The Compression deformation behavior of rubber blocks under large strain has been evaluated in this investigation. The NR/BR blended vulcanizes with different proportions of carbon black having various aspect ratios (a/h=0.5 to 1) has been examined for its compression deformation behavior under uniaxial compressive force. During the uniaxial compression of rubber blocks, a dramatic increase in the contact area has been observed in the samples, owing to higher stiffness at very larger strain the deformations is almost negligible even after increasing the compressive force. The increase in the contact surface area appeared as a rolling flow phenomenon from the load free area to the loaded area of the rubber block, and a nonlinear stress distribution was observed at all strain levels. The FEA results were compared with the experimental values and found to be in good agreement.

Key words: Compression, rubber blocks, aspect ratio, nonlinear, uniaxial deformation.

INTRODUCTION

Rubber materials are generally considered as incompressible, isotropic and hyperelastic, due to their distinctive properties in different environments. Because of these unique behaviors, rubber uses in engineering applications are unlimited. As the unique behavior of rubber materials has its own meritorious features in many applications, and the exact quantification of their behavior is comparatively difficult. Many rubber formulations are available to optimize the desired properties, and to meet a given service application (Kim & Jeong 2005). Since the currently available methods for characterizing the compressive behavior at larger strains requires more time consuming procedures, and hundreds of formulations are available in the industries for particular applications, simple and reliable methods are necessary to estimate the deformation behavior.

The figure 1 presents the un-deformed and deformed configuration of a cylindrical rubber block under normal compressive force. Where d, d_1, d_n are maximum bulge diameters at different stages. Rubber, because of its high Poisson's ratio, barrels when placed under compression in the absence of lubrication. In the testing of the mechanical behavior of rubbers, the incompressibility assumption is used to predict the deformed cross section under loading; thus, true stress was calculated (Gent 2001). At low strains, up to about 10%, linearity can be assumed for most design purposes, and products have been designed.

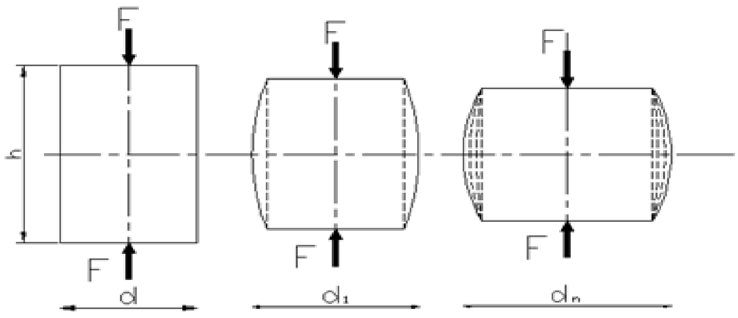

Figure 1: Deformation configuration of a cylindrical rubber block under normal compressive force

There are cases where rubbers can undergo considerable volumetric deformation under large strain applications. An elastic rubber block (spring) under vertical loading is one of the typical components where large strains are induced during their applications (Gent et al 2009). Gent (2001), in his studies, has discussed on the deformation behavior of rubber blocks and empirical relation was derived based on the assumption that the deformed cylinder has a parabolic profile under small strains. Patenadue et al (2005) evaluated the response of elastomeric blocks under large compression strains, and quantitatively measured the nonlinear behavior of rubber compounds under large strains. The true contact area and the nonlinear normal stress distribution across the sample surface have been evaluated using pressure indicating films in compression tests at different strain levels. As the behavior of the material is highly nonlinear, there is no clear definition of rubber behavior under large strain.

The assumption of a parabolic shape for the deformed cylinders under large compressive strain needs to be refined for a better approximate solution (Mott & Roland 1995, 1996). As the accuracy of an approximate solution depends on the relationship between the assumptions and the empirical determination of a nonlinear characteristic, the simplest direct experimental method to determine the nonlinear characteristics should be adopted. The investigation of the compression characteristics of rubber blocks with different aspect ratios has been carried out in the present study and is reported herein for a better understanding of their behavior.

DEFORMATION TESTING

Natural Rubber (NR) / Polybutadiene Rubber (BR) blends were compounded with N330 carbon black filler and other ingredients, according to the recipe shown in Table 1. The NR/BR blends with different proportions of carbon black were mixed in the two roll mill, and are molded in the hydraulic press. Five different proportionate of N330 Carbon black as such 0, 15, 30, 45 and 60 phr were mixed with NR/BR blend along with other ingredients, and cured as stated above, to study the effect of CB loading on the vulcanized rubber block samples under compressive loads. An identical curing procedure was followed for all the batches. The rubber compound of is placed into the mould cavity and heated to the appropriate curing temperature, and the vulcanization starts under pressure. It is desired to standardize the sample preparation procedure, so that a comparison can be made from the test pieces produced under identical conditions (Mostafa et al 2009). The NR/BR blended rubber compound of the respective batches was moulded in the hydraulic press to prepare the cylindrical vulcanizates, having various aspect ratios at 150˚C for 30 minutes. The vulcanization and shaping take place simultaneously during the moulding process. The samples were prepared from precisely designed mould and used in this study.

Table.1.Rubber Formulation

Ingredients	phr
Natural Rubber NR	80.00
Poly-Butadiene Rubber BR	20.00
6PPD[a]	2.00
Zinc oxide	5.00
Stearic acid	2.00
N330, HAF black	(variable 15,35,45,60)
Process oil (Aromatic)	5.00
Micro crystalline Wax	1.00
TBBS[b]	1.50
Sulphur	1.50

a- N(1,3-dimethyl-butyl)-N'-phenyl-p-phenylenediamine

b- N-Tertiarybutyl-2-benzothiazole sulfennamide

SAMPLE CONDITIONING

The rubber vulcanizates with different CB loading and aspect ratios has been prepared and tested for its compressive behavior. It is normal practice to adopt standard conditioning procedures, to bring the test pieces as far as possible to an equilibrium state. Rubber, especially when filled with reinforcing carbon black, softens when deformed (Diani et al 2009). This stress-softening phenomenon is widely known as the Mullins effect. One of the major difficulties in measuring the modulus in either tension or compression is its sensitivity to previous deformation (Roland 2006). Therefore, the samples have to be conditioned before testing, to get more appropriate results. ASTM D 575-91 (2001) suggests only two conditioning cycles. According to above stated ASTM standard, the rubber properties in compression have been analyzed in this study. The samples were conditioned to remove the influence of the Mullins effect before starting the test. The samples have been compressed twice at 2 hour's interval, to stabilize the stress softening effect. All test results reported herein correspond to mechanical equilibrium conditions.

The cylindrical rubber vulcanizates having different aspect ratios has been presented in the figure 2. Sample conditioning is carried out in Universal Testing Machines (AGS-2000G, Shimadzu) and brought to equilibrium state. Even though, in many situations approximate analytical solutions are introduced in deciding the material characteristics. The estimation of linear and lateral deformation of the rubber vulcanizates under uniaxial compression would be more effective, to determine the material response practically to estimates its actual behavior. While conducting the compression test, the test piece is compressed at a constant speed between the compression plates until a pre-determined strain is reached.

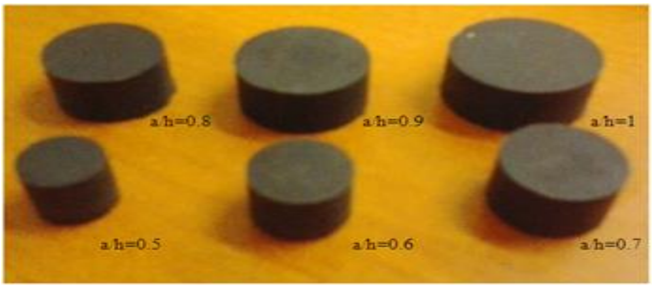

Figure 2 Images of the cylindrical samples

DEFORMATION MEASUREMENTS

An experimental setup capable of measuring bulge radius of the rubber specimen using image processing techniques was used, and large compression strain was tested (Sridharan & Sivramakrishnan, 2012, 2013). The geometric property variation was estimated using MATLAB software and the compression behavior has been investigated using the imaging techniques. The measurement obtained in this study for rubber specimens at different strain rate estimated their compression behavior. The imaging tool setup has been used for measuring the deformed cross section in this study to determine the bulge radius. The measurement of deformation behavior of rubber block is carried out in the compression fixture without slippage. The experiments were conducted on the cylindrical rubber blocks with various aspect ratios to evaluate their deformation characteristics under uniaxial compressive loads. The image of the deformed rubber block for different compressive strain was captured and further analyzed using MATLAB software.

The accuracy of the measurement from the image depends on the accuracy of calibration, illumination and the algorithm. The imaging setup has been intended for lesser perspective distortions to acquire good images. Camera calibration was carried out using a Graphical User Interface (GUI) based tool. The pixel dimensions during camera calibration were measured, with a mouse pointer positioning accuracy of ± 1 pixel. The calibration object is placed at different regions in the field of view, and the resulting multiplication factor has been averaged further, to reduce the effects of lens distortion. Better illumination has been provided in the experimental setup by using a custom made lighting. The proper threshold for the binarization of the images has been selected by a trial and error method, to ensure that none of the parts in the sample is lost as part of the background and vice versa.

FE Analysis: FEA is the versatile and comprehensive method for solving complex design problems. The rubber and rubber-like materials have been simulated by Finite Element Analysis to validate the experimental results. Material modeling is one of the important parts in the FEA procedure. The rubber blocks are commonly modeled, using solid elements with a specific isotropic hyperelastic material model (Meo et al, 2011). Even though many theoretical models were developed to characterize the mechanical behavior of rubber, one of the most important among them is the Mooney Rivlin model. This model is extensively used for the stress analysis of rubber components, and is incorporated in most commercial FEA programs. The Mooney Rivlin model with two material constants C_{10} and C_{01}, was considered in the present analysis.

MATERIAL MODEL

Rivlin and Sunders developed a hyperelastic material model for large deformations of rubber (Gent 2001). This material model is assumed to be incompressible and initially isotropic. The strain energy potential W for a Mooney-Rivlin material is given as,

$$W= C_{10} (I_1-3) + C_{01} (I_2-3) + \frac{1}{d} (J-1)^2 \quad (1)$$

where C_{10}, C_{01} and d are material constants, I_1, I_2 are the invariants of the elastic strain d=2/K, K is the bulk modulus, and J is the ratio between the deformed and un-deformed volume. This model is extensively used for the stress analysis of rubber components, and is used in the present study. When applying the finite element analysis for designing rubber products, the material constants are required as input data. To obtain sufficiently accurate material constants, combined tests and biaxial tests are recommended (Roongrote Wangkiet et al 2008). To predict the rubber behavior based on the Mooney-Rivlin model, the values of C_{01} and C_{10} has been determined. The deformation tests are usually carried out in the laboratory for determining the material behavior. The Mooney-Rivlin constants obtained from the experimental data were used in the analysis to determine the deformation behavior of rubber blocks under uniaxial compression.

The data from several modes of deformation over a wide range of strain values has been used to extract the material constants. To derive the material constants, the tests were carried out using a Universal Testing Machine (AGS-2000G, Shimadzu). To obtain the Mooney-Rivlin coefficients C_{01} and C_{10}, the deformation tests usually carried out are the uniaxial tensile test, equal biaxial tensile test, and the volumetric compression test.

Different proportions of CB filled NR/BR blends as given in the table 1were prepared and tested as per the ASTM standard. The different modes of testing were done in the above mentioned AGS-2000G machine, and the experimental data was extracted for curve fitting. The obtained data was given as input to the FE software, to extract the Mooney-Rivlin material constants C_{01} and C_{10}. Table 2 presents the Mooney-Rivlin material constants for five proportions of CB filled vulcanizates, tested under various deformation modes in the laboratory and extracted from FE software. These values were used in the FE analysis to determine the deformation characters of the uniaxially compressed rubber blocks.

Table.2.Mooney-Rivlin material constants and other material properties

Sample No.	C_{01} N/mm^2	C_{10} N/mm^2	Density ρ kg/m^3	Youngs modulus E N/mm^2
1	0.02527	0.4943	930	1.898
2	0.02085	0.5331	1010	2.050
3	0.05419	0.8503	1054	2.870
4	0.05049	1.0517	1089	3.620
5	0.09803	1.5936	1134	4.450

3D FE MODEL

3D solid models of rubber blocks with different aspect ratios were created and analyzed using ANSYS package to simulate the compression deformation and to study the stress-strain characteristics. Solid 185, CONTA174 and TARGET 170 elements are used for meshing the 3D solid model of the rubber blocks, and to define the contact conditions. Solid 185 is a structural solid used for modeling 3D solid structures. It is defined by 8 nodes having three degree of freedom at each node. These elements have plasticity, hyperelasticity, stress stiffening, creep, and large deflection capabilities. It also has a mixed formulation capability, for simulating deformations of nearly incompressible elastoplastic materials and fully incompressible hyperelastic materials. CONTA174 is a 3D, 8-node, higher order quadrilateral element used for defining the contact on a 3D solid. TARGET 170 is used to represent various 3D target surfaces for the associated contact element CONTA174. The contact elements themselves overlay the solid elements describing the boundary of the deformable body, and they are potentially in contact with the target surface. The Contact problems are highly nonlinear, and require significant computer resources to solve them. Surface-to-surface contact elements can be used to model rigid-flexible between surfaces in the present analysis. CONTA174 is a 3D, 8-node, higher order quadrilateral element, used for defining the contact on a 3-D solid.

Modeling and Meshing of Rubber Blocks: The 3D geometry of cylindrical models with different aspect (a/h 0.5 to 1) ratios was modeled along with compression platens. Figure 3 and 4 presents the 3D solid model and meshed model of the rubber block. The solid 185hex element was used to mesh the rubber block and the platens. The contacts have been defined between the rubber block and platens. TARGET 170 element was used to represent the 3D target surfaces for the associated contact element CONTA174. The Mooney Rivlin constants were assigned to the hyperelastic rubber material and compression platen with linear properties of steel. The material property of the platen material was assigned as $E=2.1x10^5$ N/mm^2, $\mu=0.3$ and ρ = 7800 kg/m^3. The respective material properties were assigned to the models, and an analysis was conducted.

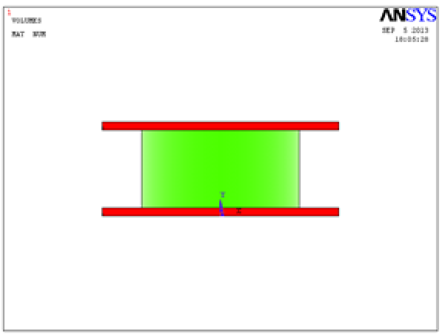
Figure.3.3D models of cylindrical samples

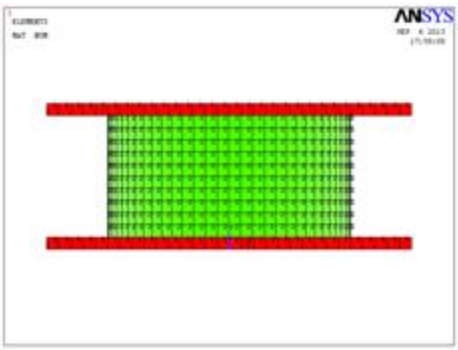
Figure.4.Meshed model of cylindrical sample

Boundary Conditions and Loads: The constraint and loading conditions on the nodes of the 3D solid are imposed to the FE model. The general Boundary conditions adopted were fixing the cylindrical rubber blocks between the platens, and compress them uniaxially. The top and bottom surfaces are in friction contact with the steel platens and the friction value has been chosen as 1 (Sridharan & Sivramakrishnan, 2014). The bottom platen is fixed, and compressive force was applied over the top surface of the platen. Different compressive loads were applied on the top platen, similar to the experiment conducted using the imaging tool, and simulation was performed. Different compressive forces were applied over the top platen, and the rubber blocks were strained. A similar analysis was performed for the cylindrical rubber blocks of various aspect ratios with their respective material properties. Thus, the simulation was carried out, using FE software to estimate the linear and lateral dimension variation.

FEA Output: Different compressive loads have been applied similar to the experimental tests, and simulation was done. The large displacement option has been selected, and the analysis was performed. FE analysis was carried out with prudence, and the obtained results are discussed in the succeeding sections in detail. Figure 5 clearly illustrates the un-deformed and deformed configurations of the rubber block under uniaxial compressive force. u_x, u_y and u_z are the displacements along the principal axes x, y and z respectively. The vertical displacement u_y represents the linear deformation, whereas u_x and u_z represent the lateral deformation.

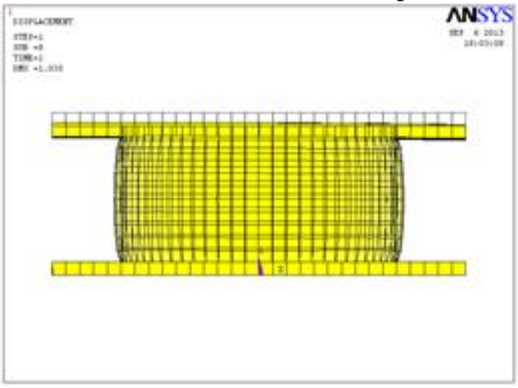

Figure.5.Un-deformed and deformed configuration of rubber block

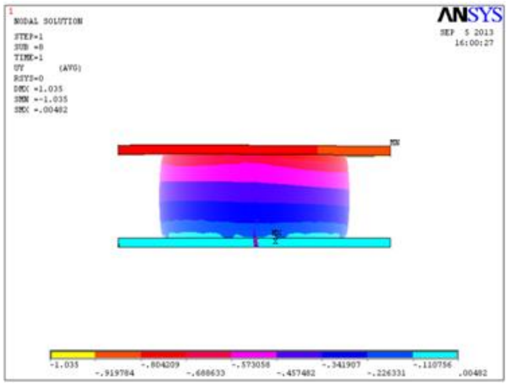

Figure.6.Deformed cylindrical rubber block

Figure 6 presents the compressive deformation of the rubber block with its vertical displacement u_y for cylindrical samples with the aspect ratio (a/h) 1. Figures 8 present the vertical displacement u_y of the deformed rubber block**.**

RESULTS AND DISCUSSION

The influence of the aspect ratio on the compressive loading of the NR/BR blended rubber samples of different aspect ratios was analyzed under uniaxial compression. The variation in the lateral and linear deformation was analyzed under uniaxial compressive force, using FEA software. Figure 7 depicts the maximum bulge radius, R_{max}, as a function of Compressive load for uniaxially Compressed CB unfilled and filled cylindrical rubber blocks of different aspect ratios. In the CB unfilled rubber block samples of low aspect ratio, the deformation behavior was highly nonlinear. As the rubber distortion is high at larger compressive force, the convergence of the solution is difficult to achieve. Owing to better dimensional stability and material property, the CB filled samples for all aspect ratios has been converged.

The maximum bulge radius values obtained for the applied compressive load, showed linear variation for all the aspect ratios. For the CB filled samples, the increase in the maximum bulge radius at the mid plane has been progressive, and showed steady bulging for all compressive loads and aspect ratios. The ultimate aim of the FE analysis conducted on the rubber cylinders of different aspect ratios using ANSYS software is to evaluate the deformed height and the increase in the lateral dimension at the mid plane.

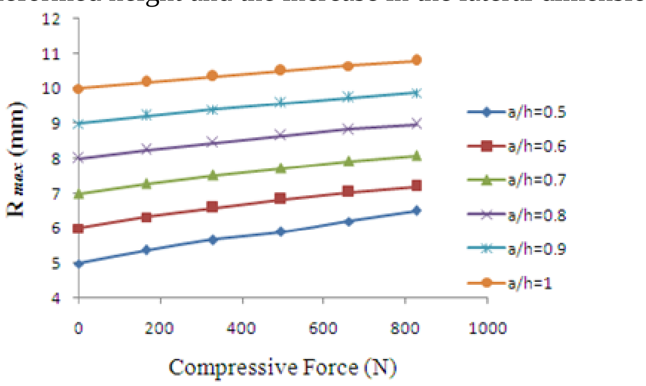

Figure 7 R_{max} as a function of Compressive force for CB filled cylindrical rubber locks of different aspect ratios

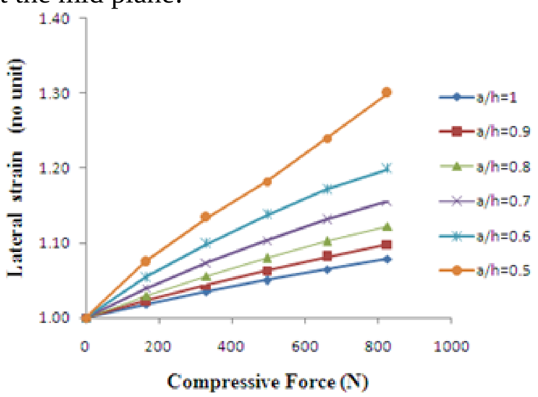

Figure 8 Lateral Strain as a function of compressive force for the CB filled cylindrical rubber blocks of different aspect ratios

Figure 8 depicts the lateral strain as a function of Compressive load for the CB filled cylindrical rubber blocks of different aspect ratios. The slender cylindrical blocks of lower aspect ratios showed comparatively uneven lateral dimension variation, under uniaxial compression. During the analysis, the lower aspect ratio samples had shown higher value for linear strains in both the CB filled and unfilled samples. Their strain behavior was also found to be nonlinear, which makes the analysis of the shape factor effect on the slender rubber blocks more significant. Thus, an extensive knowledge in acquiring the deformation characteristics of long slender rubber blocks is necessary for evaluating the nonlinear behavior in many applications.

Table.3.Comparison of Experimentally determined bulge radius R_{max} values with classical models and FEA software for CB filled rubber cylinders having a/h=0.8

	R_{max} (mm)			
Strain δl /l	Experimental	Gent Model	Mott Model	ANSYS output
0.13	8.74	8.76	8.84	8.49
0.24	9.38	9.43	9.73	9.17
0.31	9.94	9.83	10.36	9.7
0.33	10.27	9.98	10.61	10.02
0.35	10.63	10.11	10.85	10.2

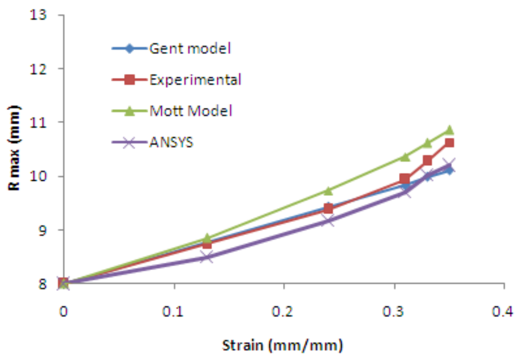

Figure.9.R_{max} as a function of strain for Rubber blocks with aspect ratio (a/h)=0.8

The comparison of R_{max} values with classical models and FEA software for CB filled NR/BR blended rubber cylinders with a/h=0.8 is presented in Table 3. The obtained value has been checked for its consistency to estimate the compression behavior of rubber blocks. Figure 9 depicts the experimentally obtained R_{max} values as a function of strain for the CB filled sample with a/h=0.8, and compared with the Gent and Mott models and also with the ANSYS software results. The Gent model has shown a linear variation in the R_{max} values for all the strain levels whereas the Mott model, FEA, and imaging tool values have shown nonlinear variation at the higher strain rate. The Experimental R_{max} values obtained using the imaging tool results are in agreement with the established models and FEA software.

When the compressive force was applied on the non-bonded cylindrical blocks of different aspect ratios, considerable increase in contact area was observed. The increase in contact area was observed in all aspect ratio samples. This is due to the fact that the free surface of the sample comes into contact with the platens. As the compressive force is increased, more and more free surfaces come in contact with the platen and the deformation appears to be nonlinear.

CONCLUSIONS

As the modeling of the compressive behavior of rubber blocks has its own practical importance in many engineering applications, the knowledge of induced compressive stress at different strain levels plays an important role in mechanically characterizing the rubber blocks. The measurement of the linear and lateral dimension variations of the vulcanizates under large strain is important to optimize their design parameters. The compressive behavior of the NR/BR blended vulcanizates with different proportions of carbon black were analyzed under large compressive strains in this study. Under uniaxial loading of the rubber vulcanizates, a substantial increase in the contact area was identified under large compressive strains for the non-bonded samples. The R_{max} values obtained experimentally were checked for their consistency with the established models, and also with the FEA results, and found to be in agreement. In the experimental and analysis buckling was observed in the unfilled and CB filled cylindrical blocks with a/h < 0.7 from aspect ratio 0.8 buckling was absent and also good dimensional stability was observed. As the precise measurement of the compression strain and its change in lateral dimension is required for a better understanding of the nonlinear behavior of the vulcanizates in many applications, it is believed that the study would be very effective and useful.

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