CHAPTER 3

EXPERIMENTAL STUDIES

Metrology is the science of measurement, including all its theoretical and practical aspects. As many of the practical applications of elastomeric materials involve compression, a precise measurement technique has been identified to estimate the compressive behavior of rubber block samples. This chapter presents the design and development of the experimental imaging tool setup for the deformation analysis of rubber blocks. In the succeeding part, the formulation and sample preparation along with the experimental analysis of the rubber vulcanizates have been extensively discussed with their significance. The details of the wear studies have been presented for a better understanding of the geometrical effect on the wear behavior.

3.1 NEED FOR IMAGE TOOL MEASUREMENT

Rubber materials are generally considered as incompressible, isotropic and hyperelastic, because of their distinctive properties in different environments. Because of these unique behaviors, rubber uses in engineering applications are unlimited. 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.

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). It is commonly accepted that while the bonded surfaces slightly influence the shear behavior of a layer, they can cause drastic changes in its compressive and bending behavior. 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 (Lindley 1979).

Patenadue et al (2005) evaluated the response of elastomeric blocks under large compression strains, and quantitatively measured the nonlinear behavior of two 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. The method was suggested for determining the change in the true contact area of non-bonded cylindrical samples to evaluate their compressive behavior. An approximate analysis for the axial compression and retraction of a rubber were conducted by Gent (2009) and the nonlinear characteristics were evaluated and Finite Element analysis was carried out to further validate the results.

In many analyses, rubber is considered as an incompressible material and analytical solutions have been provided. An appropriate nonlinear theory of elasticity has to be applied to the rubber components under large strains, for describing their mechanical behavior and it would also be more suitable for their practical applications (Koh & Lim 2001,
Tsai 2005). As the elastic layers bonded to rigid surfaces have been widely used in many engineering applications, knowledge of their actual behavior under uniaxial compressive force is essential for more precise quantification under large strains (Roland 2006). Due to constraints of analytical models at large strains, Finite Element studies were performed to evaluate the material behavior. Therefore, precise measurements of compressive deformation and variation in lateral dimension are essential, for the mechanical characterization of rubber blocks under large compression strain applications. Many of the recent studies have focused on the FE analysis procedures, to estimate the compressive behaviors of rubber materials. As the behavior of the material is highly nonlinear, there is no clear definition of rubber behavior under large strain. The investigation of the compression characteristics using a machine vision system has been carried out in the present study and is reported herein for a better understanding of compressive behavior.

3.2 FUNCTIONAL ELEMENTS OF AN INSTRUMENT

A generalized measuring system consists of the following common elements, such as the primary sensing element, variable conversion element, variable manipulation element, data transmission element, data processing element, and data presentation element. Figure 3.1 indicates the functional elements of an instrument.

The primary functional requirement of the measuring instrument is to quantitatively measure the input signal, and process it to give a useful output. The ultimate aim of the work is to measure the change in the deformation height of the uniaxially compressed rubber blocks, and their associated lateral dimension at different strains. Figure 3.1 illustrates the functional elements of the experimental setup for analyzing the deformation behavior of rubber blocks. The variables to be measured are change in height and its associated bulge area of the rubber blocks under compressive loading.
The LVDT signal and camera output are further processed to get the required output.

![Functional elements of an instrument](image)

**Figure 3.1 Functional elements of an instrument**

### 3.3 CONSTRUCTION OF AN IMAGING TOOL

An experimental setup with an imaging tool has been designed and developed for the compression and deformation analysis of rubber blocks. The setup was made rigid for better stability to withstand high compressive loads to carry out the tests. The setup included a double acting pneumatic cylinder with a control circuit, Compression set fixture, LVDT, Camera, Computer and pneumatic accessories including DCV, pressure gauges, flow control valves etc. The experimental setup to evaluate the compressive response of the rubber blocks uses the MATLAB platform for image acquisition and its processing. An algorithm has been developed for the image analysis to calculate the change in the central bulge diameter under different compressive strains. Figure 3.2 presents the schematic of the experimental setup.
Figure 3.2 Schematic of the experimental setup

3.4 GEOMETRICAL OPTICS

Image formation by lenses used in vision applications, may be explained from different perspectives. The image formation based on the projection of points from the world space to the image space, has geometrical relevance in the context of the study, while the optics treatment would help to understand the focusing and related behaviour. This section explains the image formation process from a geometrical perspective. A thin lens formulation is sufficient to explain the process of image formation by a fixed focal length lens, generally known as the prime lens (Hecht 2002). Figure 3.3 shows the basic geometry of image formation model, for focused and defocused scenarios.
Consider a thin lens of focal length $f$, when the object point $O$ is at a distance $u$ and a sharp image $O'$ is formed at a distance $v$ from the centre of the lens. The relationship between the three parameters is given by the thin lens equation, also known as the lens maker’s formula or Gaussian lens law (Hecht 2002).

$$\frac{1}{f} = \frac{1}{u} + \frac{1}{v} \quad (3.1)$$

### 3.4.1 Magnification or Scale Change

The scale or magnification of the image formed by the lens which is recorded by the CCD Camera (Charge Coupled Device) depends upon the size of the object, the distance of the object from the lens, and the distance of the sensor from the lens. Magnification is defined in different ways in different contexts. In machine vision the term primary magnification is often used to define scaling. The primary magnification of an imaging system is defined as (Hornberg 2006),
Primary Magnification = \frac{\text{Sensor size in mm}}{\text{Field of view in mm}} \quad (3.2)

### 3.4.2 Field of View and Spatial Resolution

The field of view is determined by factors such as the maximum part size, variation of the part presentation in translation and orientation, margin and aspect ratio of the camera sensor. The field of view of a lens is an open rectangular pyramid, which subtends an angle $\theta_h$ and $\theta_v$, in the horizontal and vertical planes respectively. The angles are given as follows (Hornberg 2006),

$$\theta_h = 2 \tan^{-1}\left(\frac{NS_x}{2f}\right) \quad (3.3)$$

and for the vertical direction

$$\theta_v = 2 \tan^{-1}\left(\frac{MS_y}{2f}\right) \quad (3.4)$$

where $N$ and $M$ are the number of pixels in the horizontal and vertical directions respectively. $S_x$ and $S_y$ are the sizes of a pixel in the horizontal and vertical dimensions respectively, and $f$ is the focal length of the lens.

The magnification of an image affects a parameter called spatial resolution, which is very important in any vision based application. Resolution is a measurement of the imaging system’s ability to reproduce an object detail. Spatial resolution may be considered as the resolution of the imaging system at fixed contrast, and is defined as follows (Hornberg 2006),

$$\text{Spatial Resolution } R_s = \frac{\text{Field of View in mm}}{R_c \text{ in pixels}} \quad (3.5)$$
where \( R_c \) is the sensor resolution of the camera given by the total number of pixels available along the two dimensions of the sensor.

### 3.4.3 Depth of Field

The geometry of the object causes a variation in the distance of points forming the object. This behaviour brings in the concept of Depth of Field. When the size of the lens aperture is decreased (or the \( f \)-number increased), the DOF increases and vice versa. However, the DOF does not continue to increase indefinitely. When the size of the lens aperture is decreased (or the \( f \)-number increased), the DOF increases and vice versa. However, the DOF does not continue to increase indefinitely.

### 3.4.4 Lens Distortion

The effect of lens distortion affects the magnification in the image, hence affecting the measurements taken from the images. Distortion arises, because different areas of the lens have different focal lengths and different magnifications. In the absence of other aberrations, distortion is manifest in a misshaping of the image as a whole, even though each point is sharply focussed. Distortions in machine vision cameras may be radial and tangential. Radial distortion can be felt as changes in magnification, radially out from the centre of the lens. Tangential distortions, generally known as decentring distortions arise, because of the offset of the optical elements of the lens such that they do not share the same optical axis. Such imperfections are basically due to manufacturing defects, and at the current level of lens manufacturing tolerances, tangential distortions can be safely considered as negligible (Heikkela & Siven 1997).
3.4.5 Projection Model

The ideal model of a camera with a wide angle lens such as the one used in this research is the pin-hole or the perspective camera model. Since the current research deals with 2-D measurements from the images, the camera may be modeled as a scaled orthographic projection unit. The scaled orthographic projection model is an approximate model which is often used for a system involving large working distances, compared to the heights of the objects in the scene. Generally, the working distance must be at least 20 times greater than the maximum height of an object in the scene, so that the orthographic projection model is valid. The projection equations may be defined as follows,

\[ x = sX \quad \text{and} \quad y = sY \]  \hspace{1cm} (3.6)

where \( x \) and \( y \) are the coordinates of a point in the image space which corresponds to the world point \( X, Y, Z \). In a scaled orthographic projection the non-linearity inducing factor, \( Z \) (such as in a perspective camera model) is replaced by a linear quantity’s’.

3.5 COMPONENT DESCRIPTIONS

Pneumatic control systems are widely used in the industrial sector for the purpose of automation. The designs of pneumatic components are relatively simple and they are more suitable for simple, automatic control systems. The speeds of the movement of pneumatic systems are easy to adjust; thereby the pressure and the volume of air can easily be adjusted by a pressure regulator. The different parts of the imaging tool include the Air compressor, double acting pneumatic cylinder, Camera, Light source, LVDT, pressure gauge, flow control valve, Direction control valve, platen for
Compression, Camera stand and a dedicated computer. A detailed description of the accessories used in the experimental setup is given in this section.

### 3.5.1 Air Compressor

An electrical motor drives the air compressor. The compressor can compress the air to the required pressures, and convert the mechanical energy into potential energy in the compressed air. The air inlet to the compressor is likely to be filtered, and passed via a silencer to reduce the noise level. The Filter, Regulator and Lubricator (FRL) unit is provided in the circuit for the effective functioning of the working fluid, required to actuate the pneumatic system. Figure 3.4 shows the air compressor used in the study for providing the working fluid.

![Figure 3.4 Air compressor](image)

### 3.5.2 Pneumatic Cylinder

In a double acting cylinder, air pressure is applied alternately on the relative surface of the piston for producing an extension and retraction force. A directional valve controls the direction through which the air enters and
exits the cylinder. The pneumatic cylinder acts as a linear actuator used to produce the required compressive force, and to perform deformation in the rubber samples. The choice of the cylinder is determined by the force required to move the load, and the speed required for the particular application. The double acting cylinder (Janatics - A13050025O) was used in the setup. A difference in pressure between the two sides of the cylinder results in the reciprocation of the piston. Better cushioning is provided on the inlet and outlet of the cylinder, for the steady movement of the plunger. Figure 3.5 shows the double acting cylinder pneumatic used in the setup.

![Figure 3.5 Double acting pneumatic cylinder](image)

3.5.3 Imaging Hardware

Any vision system starts with light. Lighting in a vision system can make the difference between a successful and unsuccessful application. Illumination can either enhance features to be detected or obscure them. Poorly designed lighting can produce a glare, which may saturate the camera or create shadows which can include data to be detected or obscure it. Sufficient illumination is required, because sensors are designed for the minimum amount of light required to produce signals. Proper lighting is
ensured by an optimal selection of the light source and lighting technique. The light source is a custom made Light Emitting Diode (LED). The main purpose of choosing LED is because of its DC operated nature, which ensures uniform illumination in terms of its spectral and intensity properties over time. This is mandatory, to ensure uniformity in the set of images acquired with the experimental setup. Application specific arrangements of LEDs have been developed which can be turned on and off in accordance with a sequence, that optimizes the angle of light as well as the intensity for a given image capture. The lighting technique is the geometric setup between the part, any light and the sensor (camera). The lighting technique adopted in this research may be modelled as a partially diffused bright field transmitted light. Such a technique would not have any adverse directional properties, which may cause glints in the images.

The camera used in this study is Samsung SDC-310 high resolution CCD color camera. Figure 3.6 shows the photograph of the camera used in the experimental setup. The camera is fixed in a fixture and interfaced with the computer in order to view and capture the image. The camera fixture is provided with an adjustable slot for holding the camera at a variable position, to acquire the images of the un-deformed and deformed samples. The specification of the complete imaging hardware is given in Table 3.1.

Figure 3.6 Camera
Table 3.1 Camera specification

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light Source</td>
<td>White LED</td>
</tr>
<tr>
<td>Lighting Technique</td>
<td>Partially Diffused Bright Field Transmitted</td>
</tr>
<tr>
<td>Scene Illuminance</td>
<td>160 lux</td>
</tr>
<tr>
<td>Camera Projection Model</td>
<td>Linear Orthographic projection model</td>
</tr>
<tr>
<td>Lens Focal Length</td>
<td>25 mm, CS- Mount</td>
</tr>
<tr>
<td>Aperture, f#</td>
<td>1.8</td>
</tr>
<tr>
<td>Fine Focus</td>
<td>0.25m</td>
</tr>
<tr>
<td>Working Distance</td>
<td>250 mm</td>
</tr>
<tr>
<td>Camera Model and Make</td>
<td>Samsung SDC 310</td>
</tr>
<tr>
<td>Camera Sensor Type</td>
<td>Area Scan, Monochrome</td>
</tr>
<tr>
<td>Scan Type</td>
<td>Interlaced Scan</td>
</tr>
<tr>
<td>Sensor Size &amp; Aspect Ratio</td>
<td>1/3&quot; 4:3</td>
</tr>
<tr>
<td>Sensor Resolution</td>
<td>640 × 480</td>
</tr>
<tr>
<td>Camera Output</td>
<td>Analog Video</td>
</tr>
<tr>
<td>Camera Interface</td>
<td>Analog to USB Frame Grabber</td>
</tr>
<tr>
<td>Frame Rate</td>
<td>30 fps</td>
</tr>
</tbody>
</table>

3.5.4 Linear Variable Differential Transformer (LVDT)

The Linear Variable Differential Transformer (LVDT) is one of the most widely used transducers for measuring linear displacement. LVDT is a common type of electromechanical transducer that converts the linear motion of the mechanically coupled core into the corresponding electrical signal. The deformed height of the rubber block samples was measured with a LVDT under uniaxial compressive loads. The LVDT having a stroke length of 20 mm was used in the setup which is attached along with the top platen of the compression fixture. The LVDT was fastened to the bottom of the movable
top platen attached at the end of the piston rod of the cylinder. The LVDT was attached at the top of the compression platen rigidly, and it was allowed to slide precisely in the guide way. The LVDT used in the setup for the linear deformation measurement, have an accuracy of 0.25 % Full scale. Figure 3.7 presents the picture of the LVDT used in the experimental setup, for measuring the deformation height of the compressed samples under uniaxial load.

![Figure 3.7 LVDT with display unit](image)

3.5.5 **Pressure Gauge**

The pressure of the working fluid flowing in the pneumatic cylinder was measured, using the pressure gauge fitted in the circuit. The pressure gauge is fitted in the air compressor unit shows the pressure on the working fluid available in the cylinder. The compressor having a capacity of 10 bar was used in the study for producing the working fluid, to perform the deformation analysis on the rubber blocks under normal compressive force. Figure 3.8 presents the picture of the Pressure gauge used in the experimental setup for measuring the pressure of the working fluid in the system.
3.5.6 Direction Control Valve

The function of the Directional Control Valves (DCV) is to start, stop or change the direction of flow of the compressed air into the cylinder. The DCV is used to direct the flow of the working fluid to perform the desired function in the system. The valves are not intended to vary the rate of flow of the working fluid, but are used to either completely open or completely close the flow of the working fluid, i.e. act as an on/off device. A 5/2 DCV valve is used in the setup, for providing the forward and reverse motion of the piston, which compresses the rubber samples during the forward movement. The DCV ensure the flow of air between the air ports by opening, closing and switching their internal connections. Figure 3.9 presents the image of the DCV used in the experimental setup.
3.5.7 Flow Control Valve

The flow control valve is used to control the flow of the working fluid in the system. The working fluid of the required pressure to produce the normal compressive force is allowed to flow through the flow control valve into the cylinder, to move the piston forward. When the piston moves forward, the plunger attached to the piston rod acting as a movable platen compresses the rubber block samples to produce the required deformation. Figure 3.10 presents the image of the Flow control valve used in the experimental setup.
3.5.8 Compression Platens

The compression fixture used to compress the rubber blocks, consists of two parts including a provision to hold the LVDT in the top platen. Figure 3.11 shows the picture of the compression platen used in the study. The transparent acrylic board serves as the bottom platen. An acrylic board of an inch thickness is fitted in the steel frame having good dimension stability towards all range normal compressive and shear forces.

![Compression plate (top)](image)

Figure 3.11 Compression plate (top)

3.6 IMAGE PROCESSING SOFTWARE

The imaging setup to evaluate the dynamic compressive response of the rubber blocks uses MATLAB platform for image acquisition and processing. The change in the lateral dimension measurement was coded into the MATLAB program utilizing the Image Processing Toolbox. The following section presents the details of the various software libraries used in the algorithm, developed to measure the area of the rubber blocks. The main intention of such a description is to exhibit their capabilities, and to present the actual components of the libraries used in the research.
3.6.1  MATLAB Software

MATLAB is a high-level language and interactive environment for numerical computation, visualization, and programming. MATLAB has been used for a range of applications, including image and video processing. The MATLAB language provides native support for the vector and matrix operations that are fundamental to solving engineering and scientific problems, enabling fast development and execution. In the scope of the present research, the tools from MATLAB are used for basic arithmetic and image display functions.

3.6.2  Image Acquisition Toolbox

The Image Acquisition Toolbox (IAT) enables us to acquire images from cameras and frame grabbers directly into MATLAB. The IAT automatically detects compatible image and video acquisition devices, and configures hardware properties. Advanced workflows trigger acquisition, while processing in-the-loop, performs background acquisition, and synchronizes sampling across several multimodal devices. The IAT provides an application function, and a programmatic interface to work with image acquisition hardware in MATLAB. The toolbox enables to customize the acquisition process, and to include the integrating image processing functionality to identify objects and enhance the imagery, as data is acquired. The camera is connected to the desktop computer via a USB frame grabber; hence, the ‘winvideo’ adaptor is used in the IAT.

3.6.3  Image Processing Toolbox

Image processing is the study of any algorithm that takes an image as input and returns an image as output. The Image Processing Toolbox (IPT) provides a comprehensive set of reference-standard algorithms, functions,
and applications for image processing, analysis, visualization, and algorithm development. Image enhancement, image deblurring, feature detection, noise reduction, image segmentation, geometric transformations, and image registration can be performed. In the scope of this research, the functions of the IPT are used for image cropping, thresholding and measurements. The IPT has a GUI tool called the ‘Image Tool’, which provides graphic tools such as the distance tool. The distance tool is used for camera calibration as explained in the next section.

### 3.7 CAMERA CALIBRATION

Camera calibration is the process estimation of a camera’s intrinsic, extrinsic, and lens-distortion parameters (Trucco & Verri 1998). Since the camera is modeled as a scaled orthographic projection, the intrinsic and extrinsic parameters of the camera, such as the camera pose, focal length of the lens and sensor parameters are coupled into a single quantity \( s \). Typical uses of a calibrated camera are, the correction of optical distortion artifacts, estimating the distance of an object from a camera, measuring the size of objects in an image, and constructing 3D views for augmented reality systems. A calibrated camera is mandatory to obtain any metric information of a scene.

The accuracy of the calibration depends on the following factors:

i. Accuracy of information known about the calibration object.

ii. Illumination

iii. Spatial resolution of the image

iv. Number of trials used for calibration
For any calibration, a known object is required, which in the current case is a metric ruler. Figure 3.12 presents the image of the calibration object (ruler) used for calibrating the camera. In the current study, the image of the calibration object is taken with the object located in different regions of the field of view. This is required to nullify the effects of distortion, which in the case of a radially distorted image, is predominant in the corners of the image. For each image the linear distance of a known dimension is measured in pixels as shown in Figure 3.12. The scale factor \( s \) is found based on this measurement. The scale factor \( s \) is found to be 0.054 mm/pixel in the scenario settings of the imaging hardware shown in Table 3.1. This value of \( s \) is used for all the metric conversions of the measurements from the image of the rubber blocks.

### 3.8 ALGORITHM FOR RUBBER BLOCK AREA MEASUREMENT

The image processing algorithm developed for measuring the area of the various rubber blocks, under loaded and unloaded conditions, starts with the acquisition of the image of the rubber block using the setup
exclusively developed for the purpose. The camera used in this research supports the default mode of the 8-bit RGB image. The first step in the processing addresses the conversion of the RGB image to a gray scale image. A gray scale image is nothing but the intensity values scaled in an 8-bit range. Images of this sort are composed exclusively of shades of gray, varying from black at the weakest intensity to white at the strongest. Grayscale images are distinct from one-bit black-and-white images, which in the context of imaging are images with only the two colors, black, and white (also called bi-level or binary images). Unlike an RGB image, which has three channels for every pixel, the gray scale image has only one component per pixel, which is nothing but the average of the R, G and B components in the image. The default image has many undesired regions as part of the field of view, which is suitably cropped off the image to make further processing easy. The gray scale image after undergoing the cropping operation is shown in Figure 3.13.

![Gray scale image](image.png)

**Figure 3.13 Gray scale image**

### 3.8.1 Thresholding

A binary image is a digital image that has only two possible values for each pixel. Typically the two colours used for a binary image are black
and white, though any two colours can be used. The colour used for the object(s) in the image is the foreground colour, while the rest of the image is the background colour. Binary images are also called bi-level or two-level. This means that each pixel is stored as a single bit (0 or 1).

An image is composed of light objects on a dark background in such a way, that the object and the background pixels have intensity values grouped into two dominant modes. The obvious way to extract the object from the background is to select a threshold, T that separates these modes. Then, any point \((x, y)\) in the image at which \(f(x, y) > T\) (i.e. ‘1’) is called an object point; otherwise, the point is called a background point (i.e. ‘0’). When T is a constant applicable over an entire image, the process given in the equation is referred to as global thresholding. The value of T is chosen based on the histogram of the image. When the value of T changes over an image then it is called as variable thresholding. Since there was a good constant illumination, and a high contrast between the object and the background is set deliberately, there was no need for variable thresholding. The image after the thresholding operation is shown in Figure 3.14.

![Figure 3.14 Thresholded image](image-url)
3.8.2 Image Complementing

Since the rubber blocks are dark, they constitute a low gray value; hence, after thresholding they would occupy the ‘0’ level and the background would occupy the ‘1’ level in the binary image. The convention adopted by MATLAB for the blob analysis (Region Properties Extraction) is the inverse of what was obtained after thresholding. To handle this issue, image complementing is carried out, wherein the ‘0’ level is converted to ‘1’ and vice versa, thus adhering on to the required MATLAB convention. The image after complementing the thresholded image is shown in Figure 3.15.

![Complemented Image](image)

Figure 3.15 Complemented image

Once the image is complemented, the image may be subjected some analysis of region properties, which in this research is the measurement of area of the region. Image analysis involves extracting meaningful information from an image. Pixel counting is the most basic analysis method for estimating the number of pixels in the ROI, which in fact corresponds to the area of the region in the image space. The number of pixels corresponding to the white region is counted, to ascertain the area in pixels. The actual
metric value of the area is obtained using the value of the scale factor $s$ which is obtained from the camera calibration.

3.9 DEFORMATION MEASUREMENTS

The unique behaviors of rubbers have made their engineering applications unlimited. Compression measurements of rubber cylinders are significant, to evaluate the design criteria from the past. Mott & Roland (1995), in their studies used the compression apparatus with a laser beam to analyze the uniaxial deformation of the rubber cylinders, and verified the established Gent & Lindley (1959) linear model for maximum bulge radius and engineering stress. A nonlinear model was developed to evaluate the maximum bulge radius of uniaxially compressed rubber cylinders.

An experimental setup capable of measuring a deformed cross section of the rubber specimen was developed, and large compression strain was tested (Amin et al 2003). The accuracy of the laser beam was used for measuring the deformed cross section in their studies. The measurement obtained from their studies for three different rubber specimens at different stretch rates, has proven the applicability of the device to estimate compression behavior.

The geometric property variation was modeled, and investigation has been carried out on the compression behaviors of compressible and incompressible soft spherical particles, experimentally by Yu-Li Lin et al (2008) using imaging techniques. The static compression module, using the imaging technique has been utilized for measuring the lateral surface profile of soft spherical rubber particles, to analyze the shape variation. The deformation measurement has been performed using an image analysis in the present study and reported.
3.9.1 Deformation Testing Tool

A Camera, light sources and the samples were carefully positioned in the setup to get precise measurements. The pneumatic control setup with accessories was mounted, for the effective functioning of the system. A rubber block was placed above the bottom platen, and the image of the undeformed sample was acquired. The plunger compresses the rubber cylinders under variable pressure loads and the uniaxial deformation was recorded. The deformed height of the samples was measured more accurately by a LVDT, which is attached to the top platen. The Camera is fixed in position and interfaced with the computer, in order to view and capture the image. Effective LED light sources have been provided for better illumination to get a quality image.

The experimental setup to evaluate the dynamic compressive response of the rubber blocks uses MATLAB software for image acquisition and its processing. An algorithm has been developed for the image analysis, to calculate the change in the central bulge diameter under different compressive strains. Figure 3.16 shows a complete experimental set up used in the investigation. The images of the lateral dimensions of the compressed rubber blocks were captured utilizing the MATLAB image processing toolbox. The loading arrangement was changed, and shear force was applied on the rubber samples to estimate the shear characteristics. The picture of the shear loading setup has been presented in Figure 3.17. A similar testing procedure was followed as the compressive loading and shear behavior of the rubber blocks were evaluated. The shear loading fixture was mounted in the setup to perform the shear deformation analysis on the rubber blocks.
Figure 3.16 Experimental setup

Figure 3.17 Shear load setup
3.9.2 Measurements Uncertainties

Uncertainty of measurement is the doubt that exists about the result of any measurement. Since there is always a margin of doubt about any measurement, it is necessary to quantify how big the margin is. When conclusions are drawn from the measurement results, the uncertainty of the measurements must not be forgotten. To calculate the uncertainty of a measurement, the sources of uncertainty in the measurement must be identified, and then, the size of the uncertainty from each source must be estimated. Finally, the individual uncertainties are combined to give the overall figure. The compressive force exerted on the movable top platen serves as an input to the LVDT to measure the deformed height of the rubber blocks. The images were captured by the camera for the corresponding linear deformation developed by the compressive loads on the rubber blocks. Thus the calibrations of the linear and lateral measuring devices are very important to decide the accuracy of the measured quantities.

3.9.3 Measurement Accuracy

The accuracy of the measurement from the image depends on the accuracy of calibration, illumination and the algorithm. The image tool has been designed and developed by considering the above facts. 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. The LVDT used in the setup for the linear deformation measurement has an accuracy of 0.25 % for full stroke length of 20 mm.

The deformed height from the LVDT, and the associated variation in the lateral dimensions for the corresponding height recorded using the camera, were analyzed to estimate the compressive behavior of the rubber blocks under uniaxial loading. Moreover, the reliability of the testing tool measurements was validated with the established analytical models and FEA software results, and shown to have good agreement. The observed experimental tool readings were in concord with the analytical models and FEA output.

### 3.9.4 Compression Testing of the Vulcanizates

The experiments were conducted on the non-bonded and bonded cylindrical rubber blocks with various aspect ratios, and rubber blocks with different geometrical shapes, to evaluate their deformation characteristics under uniaxial compressive loads. The working fluid was compressed to the required pressure in the compressor cylinder. The pneumatic circuit was checked for its effective functioning. Proper lighting was provided for better illumination. The rubber block was placed over the transparent acrylic bottom platen, and the camera was positioned to get more precise image of the undeformed rubber block. The flow control valve was adjusted to regulate the flow of the working fluid.

The DCV position was changed to move the piston forward and to exert the necessary compressive force on the rubber block. When the top platen compressed the rubber block, the linear deformation was recorded from the LVDT digital display. The image of the deformed rubber block for the corresponding compressive strain was captured. The linear deformation from
the LVDT, and the associated variation in lateral dimensions recorded as an image were further analyzed using MATLAB software.

3.10 DEFORMATION STUDIES

Vulcanized rubber being complex material exhibiting a unique combination of properties, subjected to various test methods relevant to particular applications. Virtually, infinite numbers of rubber compounds are in practical usage, each with its own detailed vulcanizate characteristics. Many variations in compounds with different vulcanizate properties are possible, and thence one must evaluate every vulcanizate to meet the specification. With such unusual and complicated materials, the procedures used for measuring their properties often differ from common methodologies (Roger Brown 2006). In this section, the preparation of the rubber samples, development of rubber compounds and the experimental testing of vulcanizates for their compressive behavior are listed.

3.10.1 Mould Design

Rubber products are mostly moulded using compression moulding techniques, and the design of mould for the elastomers has decisive influence on the product. It is necessary to use more precisely designed and well constructed steel moulds, suitably hardened and finished for moulding the samples. Care has to be taken in the mould design and manufacture depending upon the surface quality required in the product. In this investigation, the samples were prepared, using the compression moulding process. To ensure dimensional consistency in the samples, it is necessary to allow the excess material to move away from the edge of the cavity, so that the land between the cavities can contact with minimum flash. The moulds used in this investigation are made of die steel, and fabricated by using the wire cut Electrical Discharge Machining (EDM) process to ensure good dimensional
accuracy. Adequate care was taken in designing the mould for getting almost flash free samples. The mould cavities for cylindrical and other different geometries have been precisely machined in EDM to ensure more accurate dimensions in the samples.

Moulds were designed using AutoCAD software. All the geometries in the mould are designed to represent a broad range of tyre tread blocks. To study the geometrical effects of rubber blocks under compressive and shear loading, all the samples were made identical, in terms of mass and volume. The samples were modeled, such that they have the same contact area, depth, identical mass and volumetric property, to study the effect of change in contact geometry under uniaxial compression and shear deformation.

(a)

Figure 3.18 (Continued)
Figure 3.18 CAD model and picture of the moulds (a) CAD model (b) Mould for different geometries (c) Mould for cylindrical samples

Figure 3.18 (a) presents the CAD model of the mould in millimeter and used in this study. The regular geometries such as circle, square and rectangle along with other profiled geometries, as shown in Figure 3.18 (a), have been modeled and fabricated. Figure 3.18 (b) and (c) show the images of
the moulds fabricated for different geometries and cylindrical geometries used in this study.

3.11 RUBBER FORMULATION

Raw gum elastomers by themselves have very limited use, as most of them are mechanically weak, liable to significant swelling in liquids, and will not retain their shape after molding. The gum elastomer, therefore, has to be mixed with the necessary additives, in order to vulcanize it under suitable temperature and pressure. So, a rubber compound consisting of all the necessary ingredients has to be developed. The term phr (parts per hundred), meaning parts of any non rubbery material per hundred parts of raw gum elastomer (rubbery material) is used to represent any formulation. It is preferred, rather than expressing an ingredient as a percentage of the total compound weight. Parts can mean any unit of weight used throughout the formulation.

Rubber compounds are generally composed of a base rubber, filler, e.g. carbon black, and curing agents. Additional components may include antioxidants, adhesion agents, flame retardant agents and special process-enhancing additives. Every ingredient of a rubber recipe may affect these physical properties. The mixing and curing process are also critical in determining these properties. Changes to improve one property may affect other properties in either a positive or a negative manner, so that care has to be taken to present an optimum formulation adhering to all the aspects.

3.11.1 Rubber Blends

A single raw gum elastomer, very often might not give the combination of properties required for a specific application, and thus different elastomers need to be blended. The use of rubber blends is an
effective method for altering the performance properties. NR is an ideal elastomer, suitable for most general purposes and engineering applications. However, the most important aspect of NR is that, it is environment friendly. Most engineering applications of NR involve its use as a spring. The main reasons for using NR in springs are, its excellent resistance to fatigue, cut growth and tearing, low heat build-up, good bonding with metals/fibres, and high resilience. With its unique and excellent properties, NR is utilized in tyres, shock mounts, seals, isolators, couplings, bridge bearings, building bearings, footwear, hoses, conveyor belts, plant linings, and many other moulding applications.

The blending of polymers has become an increasingly important area of research activity. Elastomer blends are used for many reasons, such as lowering the compound cost; ease of fabrication and to improve the performance of the industrial rubber. Findik et al (2004), in their investigation of the mechanical and physical properties of several industrial rubbers, studied the properties of NR/SBR. 12 different rubber compounds were prepared, by using SMR-20 type of natural rubber and SBR-1502 type of styrene-butadiene rubber in different proportions and their mechanical and physical properties are studied.

PolyButadiene (BR) blended with NR is mostly used for heavy duty truck tyre applications, as it can reduce the heat build-up and improve the abrasion resistance of the tyre. To achieve a combination of strength and very high resilience, a blend of BR with NR could be used (Kim & Jeong 2005). The NR/BR blended rubber has its own application in many rubber products, including tyres and they have been opted for analyzing its deformation behavior under normal compressive and shear force. The NR/BR blended rubber vulcanizates, similar to tyre tread blocks was molded and tested in this study, and their deformation behavior has been reported.
3.11.2 Other Ingredients in the Formulation

Carbon black is the most commonly used filler for rubber compounds and has been in constant use in formulations. It is more often added to improve the physical properties (e.g., tensile strength, hardness and tear strength) of a rubber compound. Carbon black is an extremely pure form of carbon, which consists of very small, mostly spherical particles which fuse together in clusters referred to as aggregates. The aggregates themselves group together as agglomerates, which break up during the mixing process. The aggregates tend to remain intact in the rubber matrix, and the type of aggregate defines the structure of a carbon black.

Sulphur reacts chemically with raw gum elastomer, forming cross-links between the polymer chains, resulting in a more dimensionally stable and less heat-sensitive product. Zinc oxide and stearic acid together with sulfur and accelerator constitute the cure system for the formulation. Zinc oxide reacts with stearic acid to form zinc stearate, and together with the accelerator it speeds up the rate at which sulfur vulcanization occurs. With sulfur alone, the curing process might take hours. With this curing system, it can be reduced to a few minutes. Petroleum oils are offered to the rubber industry to meet two basic processing and compound requirements. They act as a processing additive or rubber extender, and softener. The classification depends upon the oil volume added to the rubber compound. As processing additives the oil addition level is usually no more than 5-10 phr.

Wax is added as an antioxidant to the rubber compound, depending upon a number of factors, such as the type of rubber being protected, temperature, type of service, effect of filler, etc. The solubility of wax in vulcanised rubbers is low (of the order of 0.5% for NR) but enough wax has to be added to a rubber compound to ensure that once the compound, has been vulcanised and the rubber cools, the rate of the migrational movement of the
wax from the rubber mass to the surface of the rubber is rapid. Microcrystalline waxes form smaller crystals, which pack tighter together to form a more coherent and more flexible film on the rubber surface, which is more resistant to ozone penetration. The standard rubber formulation with all the additives used in this study, has been presented in Table 3.2.

### Table 3.2 Rubber Formulation

<table>
<thead>
<tr>
<th>Ingredients</th>
<th>phr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural Rubber (NR)</td>
<td>80.00</td>
</tr>
<tr>
<td>Poly-Butadiene Rubber (BR)</td>
<td>20.00</td>
</tr>
<tr>
<td>6PPDa</td>
<td>2.00</td>
</tr>
<tr>
<td>Zinc oxide</td>
<td>5.00</td>
</tr>
<tr>
<td>Stearic acid</td>
<td>2.00</td>
</tr>
<tr>
<td>N330, HAF black (variable 15,35,45,60)</td>
<td></td>
</tr>
<tr>
<td>Process oil (Aromatic)</td>
<td>5.00</td>
</tr>
<tr>
<td>Micro crystalline Wax</td>
<td>1.00</td>
</tr>
<tr>
<td>TBBSbb</td>
<td>1.50</td>
</tr>
<tr>
<td>Sulphur</td>
<td>1.50</td>
</tr>
</tbody>
</table>

*a* - \( \text{N}(1,3\text{-dimethyl-butyl})-\text{N}^\prime\text{-phenyl-p-phenylenediamine} \\
*b* - \( \text{N\text{-Tertiarybutyl-2-benzothiazole sulfennamide}} \)

#### 3.11.3 Carbon Black

Fillers are used in rubbers for various purposes. In fact, reinforcing fillers, when added to an elastomer, can provide a composite product with very high strength. Carbon black is used as the most important filler in the rubber industry. Fillers such as carbon black are added in order to increase the stiffness of the material or, in some applications, to increase the resistance to wear. The filler and the elastomeric material are not chemically joined; they are separate phases in the vulcanized rubber, connected only by physical
forces and contact. The rubber phase forms a continuous network through the filler material, and forms agglomerates inside the rubber network. The material is thus a two-phase material made from constituents with completely different mechanical properties. The mechanism of the reinforcement is believed to be both chemical and physical in nature. Its primary properties are surface area and structure, which affect the physical properties of the vulcanized rubber product. Smaller particle size blacks having a higher surface area give a greater reinforcing effect. Increased surface area gives increased tensile, modulus, hardness, abrasion resistance, tear strength, electrical conductivity, and decreased resilience and flex fatigue life.

Good carbon black dispersion in rubber is an important factor to realize the full reinforcement potential of carbon black. Inadequate dispersion generally results in poor physical properties, or poor processing. Mostafa et al (2009) studied the effect of carbon black loading on the swelling and compression set behavior of SBR and NBR compounds. Five different compositions for SBR and NBR with 0, 20, 30, 50 and 70 phr of CB were compared. From the investigation it was found that, the increase in carbon black loading led to drastic reduction in the swelling percentage, while the compression set increases in both the SBR-filled compounds and NBR-filled compounds.

The reinforcement of rubber by rigid entities, such as carbon black has been found to offer substantial improvement in the mechanical properties of rubber, because it has very good compatibility with rubbers (Anqiang et al 2003). Carbon black was added to rubber formulations to optimize properties that meet a given service application (Ismail Hanafi & Anuar 2000, Kim & Jeong 2005). The Rubber Formulation with different proportions of carbon black has been presented in Table 3.2. The carbon black was mixed in five different proportions with the NR/BR blend, along with other ingredients for each batch separately, to estimate their physical properties.
3.12 MIXING AND VULCANIZATION

Natural Rubber (NR) / Polybutadiene Rubber (BR) blends were compounded with N330 carbon black filler and other ingredients, according to the recipe shown in Table 3.2. The NR/BR blend with different proportions of carbon black was mixed in the two roll mill, and samples 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 NR/BR blended rubber compound of the respective batches was moulded in the hydraulic press to prepare the cylindrical vulcanizates, having various aspect ratios and other different shapes at 150°C for 30 minutes.

Vulcanization and shaping take place simultaneously during the moulding process. The rubber-filler mix is placed into the mould cavity and heated to the appropriate curing temperature, and the vulcanization starts under pressure. The curing time is dependent on the temperature, the size of the product and on how well heat is transferred to the product. The press used for compression moulding is substantially constructed, and has two platens which are heated electrically. The platens are brought together by hydraulic force. The samples used in the study are cured in the hydraulic press for a curing time of 30 minutes at 150°C.

3.13 RUBBER BLOCK SAMPLES

The test pieces were prepared directly by moulding in the hydraulic press. The properties of the test samples and hence the test results obtained will depend on the processing methods. It is highly desirable to standardize the sample preparation procedure, so that a comparison can be made from the
test pieces produced under identical conditions. The dimensions of the samples play a critical role as it is very likely to influence the results. As the test results are sensitive to the geometry of the test piece and also, different geometries were used in this analysis to estimate the deformation behavior, the test pieces were prepared very carefully. Figure 3.19 classifies the rubber block samples used in this investigation. The cylindrical samples with aspect ratios (a/h) ranging from 0.5 to 1 are analyzed with and without the CB filler. Also, cylindrical rubber blocks were bonded between steel plates on the top and bottom surfaces, and compressive force was applied to study their deformation behavior.

![Image of NR/BR blended Rubber block](image.png)

Figure 3.19 Classifications of rubber block samples

![Images of the non-bonded cylindrical samples](image.png)

Figure 3.20 Images of the non-bonded cylindrical samples
The modeling of the compressive behavior of rubber blocks has its own practical importance in many engineering applications. The deformation phenomenon was studied on the cylindrical rubber samples. The samples were prepared from precisely designed moulds, and used in the studies. The non-bonded cylindrical rubber vulcanizates having different aspect ratios ranging from 0.5 to 1 were used to study their deformation characteristics under uniaxial compressive force, and are presented in the Figure 3.20.

3.13.1 Bonded Rubber Blocks

The engineering applications of rubber components are mostly composed of both rubber and steel. The steel parts bonded with the rubber part are used to connect the rubber unit to other structures, or to increase the stiffness of the unit. The steel parts are bonded very efficiently to the rubber using adhesives. The adhesive bond is stronger than the cohesive strength of the rubber material, in the sense that a rupture in a manufactured rubber-steel unit usually occurs in the rubber, and not at the bonding surface between the rubber and the steel. Figure 3.21 presents images of the bonded cylindrical vulcanizates having different aspect ratios.

![Figure 3.21 Images of the bonded cylindrical samples](image-url)
Post Vulcanisation bonding (PV bonding) is a specialized method in the rubber to metal bonding process. For PV bonding, the adhesive is applied to the metal, just as for vulcanisation bonding. To achieve good long-lasting bonds between rubber and metals, it is essential that both materials presented to the interface be clean and free from detritus. The steel substrates were suitably pre-treated to achieve satisfactory bonding with the rubbers. Mechanical treatments, such as buffing, degreasing and cleaning were followed to prepare the metal surfaces.

The Cyanoacrylate adhesive offers an unbeatable combination of speed, simplicity and strength, particularly to join widely different materials. The steel plates having 2 mm thickness were coated with the adhesive to bond with rubber. The rubber blocks was then put in contact with the adhesive coated metal, using tooling fixtures to position the rubber and hold it in place. A compressive force is then applied to keep the surfaces in intimate contact until a bond is formed.

### 3.13.2 Tread Block Geometries

Different models of rubber blocks with an exact depiction of the tyre tread block were moulded in the hydraulic press. A single tread block sample has been investigated for the deformation behavior under normal compressive and shear force. The samples with and without the CB filler were moulded similar to the cylindrical samples, and used for the deformation analysis. The tread block samples were compressed by normal and tangential forces and their deformation behavior was observed in terms of change in the contact area and bulge area at the mid-plane. The images of the vulcanizates of different geometries similar to the tyre tread block are presented in the Figure 3.22.
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 (Mullins et al 1967, 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. 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.

3.15 DEFORMATION TESTING

Rubber products are most widely used in engineering applications where the modes of loading are predominantly compressive and shear by
nature. The engineer recognizes this, and uses this property for the design and development of rubber products. In the testing of rubber, different test methods and different specifications are available (Dick 1995). The operating cost of the testing would be significantly high, if more standards are to be met for a particular property. On the other hand, if a common standard has been followed on the same target values, the testing costs would be greatly reduced. There would be a significant reduction in the number of tests to perform, and this would reduce the frequency of testing.

3.15.1 Compressive Deformation

The measurement of the deformation behavior of a uniaxially compressed rubber block in the compression fixture without slippage is required for its mechanical characterization. Under compressive deformation, strain is induced parallel to the direction of displacement that results in a decrease in the height of the body. The compression modulus is the material property defined as a resistance to change in height, when subjected to a compressive force (ratio of compressive stress to compressive strain). It has been established that the pressure method can accurately predict the linear behavior of bonded elastic layers under uniform compression/pure bending for a high shape factor, layers of incompressible materials (Koh & Kelly 1989).

In the present study, the deformation behavior was analyzed applying compressive force uniaxially on the rubber blocks. In a compression test, the test piece (lubricated or bonded) is compressed at a constant speed between the compression plates until a pre-determined strain is reached. Rubber is essentially an incompressible material that deflects, by changing its shape rather than by changing its volume. If rubber is physically restrained from bulging and by applying compressive force, its compression modulus would be extremely high, as the rubber is virtually incompressible.
The compression tests are usually carried out in Universal Testing Machines and their stress-strain behaviors are studied. But, in many situations approximate analytical solutions are introduced in deciding the material characteristics. As the accuracy of the analytical relation depends on the assumptions and methodologies on which it has been derived, a more appropriate laboratory test method is needed, to meet the current demand for rapid testing of compressive behavior than to simply rely on the analytical estimation. The simultaneous estimation of linear and lateral deformation of the rubber vulcanizates under uniaxial compression would be more effective, to determine the material response practically. Thus, the developed image tool will satisfy the requirement to study the deformation behavior of rubber blocks under dynamic stressing, to estimate their compressive behavior.

3.15.2 Determination of Maximum Bulge Radius

Many of the test results are sensitive to the geometry of the test piece and the cylindrical geometry is chosen for analyzing the compressive deformation phenomenon in the image tool. The obtained results such as the deformed height, bulge radius and the low intensity band formed at intermediate strain were necessary to characterize the deformation behavior. The images of the deformed cylinders was captured under various strain levels, and analyzed for the maximum bulge radius. A similar procedure has been followed to determine the bulge radius of the different aspect ratio cylinders, unfilled and filled with carbon black. The cylindrical rubber samples were bonded with steel plates, and compressed uniaxially similar to the non-bonded samples, and the images were captured. The variation in the bulge radius at different compressive strains was computed from the images, using MATLAB software.

The cylindrical and other geometrical rubber blocks were moulded under identical conditions and compression tests were performed to estimate
the deformation. A common test procedure was followed to determine the compression response of non-bonded and bonded rubber blocks. The cylindrical rubber samples of different aspect ratios (a/h) were compressed uniaxially, and the maximum bulge radius at the mid plane was evaluated. The compressive force was applied over the top face of the cylindrical rubber block to compress it. The linear and lateral dimension variations were recorded by the LVDT and the images respectively. The plunger was adjusted to move very slowly and precisely to achieve uniform loading. The plunger rate for the applied pressure load varied from 0.4 to 1 mm/sec. The images of the deformed samples were captured, using the image acquisition toolbox and the images were processed by using the image analysis toolbox in MATLAB.

![Un-deformed block](image1.png) ![Deformed block](image2.png)  
**Figure 3.23 Images of the un-deformed and deformed rubber blocks**
(a) Non-bonded cylinder  
(b) Bonded cylinder
The images of the un-deformed and deformed geometry of non-bonded and bonded cylindrical samples have been presented in Figure 3.23 (a) and (b). The compressive force was applied from the upper platen on the top surface of the samples to deform them. The measurement of linear deformation (change in height) was made by the LVDT. The images of the deformed rubber blocks were captured, using the MATLAB image acquisition tool box, and analyzed for evaluating the variation in the lateral dimensions.

### 3.15.3 Behavior of the Rubber Blocks of Different Geometries

A similar analysis was performed on rubber blocks whose geometry is similar to the tyre tread, and the compressive deformation behavior was analyzed. The un-deformed and deformed geometry of the square and rectangular samples is presented in Figure 3.24 (a) and (b). From the images obtained for the regular cylindrical, square and rectangular geometry, the deformation was found to be symmetric under normal compressive force.

The deformation phenomenon was observed to be common, and the compression behavior was identical under all normal loadings. But, a significant variation in the strain level is observed between the CB filled and unfilled samples under all compressive loadings due to variation in the stiffness. The deformation phenomenon was found to be common in the CB filled cylindrical vulcanizates, showing symmetrical bulging. Also, beyond 50 percent of linear deformation, the dimensional variation was found to be almost negligible, and the vulcanizate became highly stiff.

From the investigation, it was inferred that the regular circular and square shaped blocks bulge uniformly outwards for all the normal compressive forces and the bulging also progressively increased upon increasing the magnitude of the compressive force, as shown in Figure 3.24. The un-deformed and deformed geometry of mixed pattern samples which
replicates the actual tread block geometry is presented in Figure 3.25. In the case of the mixed pattern rubber blocks, the bulging appeared in a distinguished manner.

![Un-deformed Square block](image1) ![Deformed Square block](image2)
(a)

![Un-deformed rectangular block](image3) ![Deformed rectangular block](image4)
(b)

**Figure 3.24** Images of un-deformed and deformed non-bonded rubber blocks (a) Square shaped block (b) Rectangular shaped block

In the analysis of mixed patterns, which have more applications in tyre treads, the following inferences were drawn. The compressive deformation characteristics varied from the regular geometry, and a distinguished change was noted in the contact patch. As the rubber block was modeled as such their contact areas are the same for all the patterns. The variation of the contact geometry of the rubber blocks showed a noticeable
deformation in the contact patch. The argument of the distinguished geometry of the tread block in the contact patch and its deformation effects has to be studied extensively to optimize the tyre design. Figure 3.25 presents the undeformed and deformed geometry of rubber blocks. The combination of convex/concave shapes in the pattern tends to bulge out in a different manner, as shown in Figure 3.25 (a) and (b). The deformation formed on the load free area, tends to pull out the material from the concave/convex edge, to make it bulge under large compressive strains. The shorter edges in the tread block patterns tend to suffer higher distortion along with the longer edges under compressive force; also, the block bulging was not uniform at higher strains.

Figure 3.25 Images of un-deformed and deformed rubber blocks
(a) Mixed pattern block-1 (b) Mixed pattern block-2
A shear deformation study was performed on the rubber blocks, similar to the compression studies. The shear force was applied on the rubber blocks by changing the compression fixture in the experimental setup. An analysis was performed on the non-bonded rubber vulcanizates under shear loading, in the absence of lubrication. It has been observed that the shear loading showing a distinct variation, in the rubber block deformations exhibiting highly nonlinear behavior. An extensive discussion of the observation made during the analysis of compressive deformation, and the results obtained from the image tool, are given in the ‘result and discussion’ chapter.

3.16 WEAR ANALYSIS

Abrasion is a phenomenon of material removal from a surface, due to an interaction with another surface. This phenomenon takes place in almost all the elastomer components, especially in car tyres, conveyer belts, printing rolls, and shoe soles. The abrasion or wear rate is the dominant factor that controls the service life of all these components. Abrasion or wear rate are therefore important factors in determining how fast the material is removed from the surface for determining a component’s life.

As good abrasion resistance has become a high priority for most elastomer components, wear studies were performed on the vulcanizates with standard rubber formulation, and presented in Table 3.2. The shape effects on the wear characteristics were assessed for the vulcanizates of different geometries. The wear test has been conducted in the DIN Abrader for estimating the wear characteristics. The DIN abrader is a device used for estimating the wear of vulcanizates, following the DIN standard (DIN 53516). Figure 3.26 (a) and (b) shows the CAD model of the mould in millimeter units for moulding the wear test samples used for the wear studies.
Figure 3.26 CAD model of wear test samples (a) short edge samples (b) Projected edge samples
3.16.1 Sample Preparation and Wear Assessment

The samples have been prepared from specifically designed moulds, for evaluating the wear properties of NR/BR blended rubber vulcanizates. Varieties of tread block geometries and patterns are available in a tyre, out of which some of the regular geometries, such as square, rectangular and cylindrical along with two others have been chosen in this study. The mould includes two parts, the upper part with regular cylindrical shaped cavities, and the lower part has cavities similar to the tread block geometries. Since the standard chuck is designed for holding the cylindrical samples in the DIN abrader machine, the mould is specifically designed with two parts to satisfy this above purpose. Figure 3.27 shows the picture of the mould used for the wear studies.

![Mould for wear studies](image)

The moulding was carried out in the hydraulic press at 150°C for 30 minutes. The base of the sample is cylindrical in shape with a diameter of 16 mm, for holding it in the chuck. All the samples are designed to have a total height of 12 mm base with 2 mm treads. A picture of the vulcanizates used for wear studies is presented in Figure 3.28 (a) and (b).
Rubber block sample sets of different geometries have been tested for wear in the DIN abrader under standard conditions. A load setting with 5N has been setup on the samples, and the abrasion test was conducted for a total length of 40 m abrasion run as per the standard test method. The Mass loss has been calculated for the rubber blocks with different tread geometries. The abrasion patterns formed as parallel ridges on the surface, and the wear characteristics of different shaped rubber blocks are recorded.