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SHORT ARTICLE

Detection of Material Fatigue in Polyvinyl Chloride (PVC) for Bouncy Castle Application

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Abstract:

The creation and design of a conceptual electronic and electromechanical equipment setup for material fatigue detection in Bouncy Castles made of polyvinyl chloride (PVC) material is what we suggest in this work. By utilising this cutting-edge equipment setup, which includes what we call a Camera Columnar System (CCS) that operates on the Fourier Transform Infrared Spectroscopy (FTIR) principle mounted on an Electro-Mechanical Conveyor System (EMCS), we can apply targeted material analysis while kids are actively playing on the Bouncy Castles. To identify any anomaly or variation, the PVC's FTIR map distributed band spectrum displayed on the CCS/EMCS are compared with FTIR spectrum of pure PVC stored in the equipment's memory. From the results obtained by this comparison, if an anomaly or variation is found, this we suggest could be a sign of material fatigue brought on over time by stress, strain, photodegradation, and environmental temperature fluctuations. We believe that this CCS/EMCS proposed concept will aid in reducing accidents and fatality.

Keywords: Bouncy Castle, Polyvinyl Chloride PVC, Fourier transform Infrared Spectroscopy FTIR, Camera Columnar System CCS and Electromechanical Conveyor system.

Introduction

The demand for Bouncy Castle especially for outdoor events has significantly increased throughout the summer months all around the world mainly in Europe, America, and Australia. According to recent statistics, 44% of outdoor events are held between June and September each year, putting additional stress and strain on Bouncy Castles thereby resulting in catastrophic accidents and fatalities (1-5). An accident happened in Russia involving a Bouncy Castle that burst and sent children "flying over a metal fence," according to an account from the Daily Mail(6). Eyewitnesses reported there was no wind and heard an explosion before watching the Bouncy Castle soar into the air (6). According to the Daily Mail, the material fall might have been caused by the Bouncy Castle being overinflated, as well as the fabric deterioration of the Bouncy Castle rubbing against the tarmac. Both of these factors could have contributed to the collapse. In a related incident in Spain (7) A six year old girl lost her life in this incident. It has been suggested that a valve on the inflatable malfunctioned, enabling pressure to build up and ultimately causing an explosion, of which several children were launched into the air at great heights before being dropped onto the asphalt or grass below(7).

Similarly, in Newcastle, a three year old toddler sustained severe life-threatening injuries after an accident involving a Bouncy Castle (8). However, she was saved by quick response from the paramedics. Moreover, in a similar incidence, more than twelve people got injured with two fatalities when an inflatable structure like a Bouncy Castle was tossed into the air by gusty winds. An eye witness account reported seeing a human figure plunge from twenty feet to the ground (9). Additionally, two fairground staff members have been convicted for gross negligence and dereliction of duty, when a Bouncy Castle accident caused a seven year old girl to be flung over three hundred meters away from the fairground due to poor anchoring of the Bouncy Castle when gusty winds started blowing (10). According to the British Standard BS EN14960:2013 any inflatable used for commercial purposes in the United Kingdom must adhere to the standards such as general condition of the Bouncy Castle, installation process, number and locations of those anchor points and wind speeds (11). Furthermore, regulations also suggest air pressure by maintained within approved limit (12). If this limit is exceeded over time, irregular straining and stretching of PVC material is noticeable.

In this paper, we are proposing a conceptual system having an infrared based camera (13) positioned some distance around the periphery of the Bouncy Castle monitoring with a view to detecting material fatigue. The FTIR spectrum of pure PVC (14-15) which is stored in the memory of CCS contraption is then matched in real time readings as the CCS scans the Bouncy Castle and any variation is flagged as a buzzing sound. This conceptual equipment setup drawing is seen in Fig1. PVC are most widely used in the manufacture of plastics which can be molded into different structures. They are affordably priced and extremely resistant to corrosive agents and chemicals in severe situations. Dehydrochlorination during the extrusion process, photo-degradation, and temperatures beyond 100^{o}C (16-20), causes PVC material to attain an unstable structure by the formation of polyenes containing conjugated Carbon-Carbon(C=C) double bonds (15) and (16). As such, dehydrochlorination leads to deterioration in the thermal and physical properties of PVC coupled with discoloration which in inappropriate for Bouncy Castle usage (11-12) and (19-20).

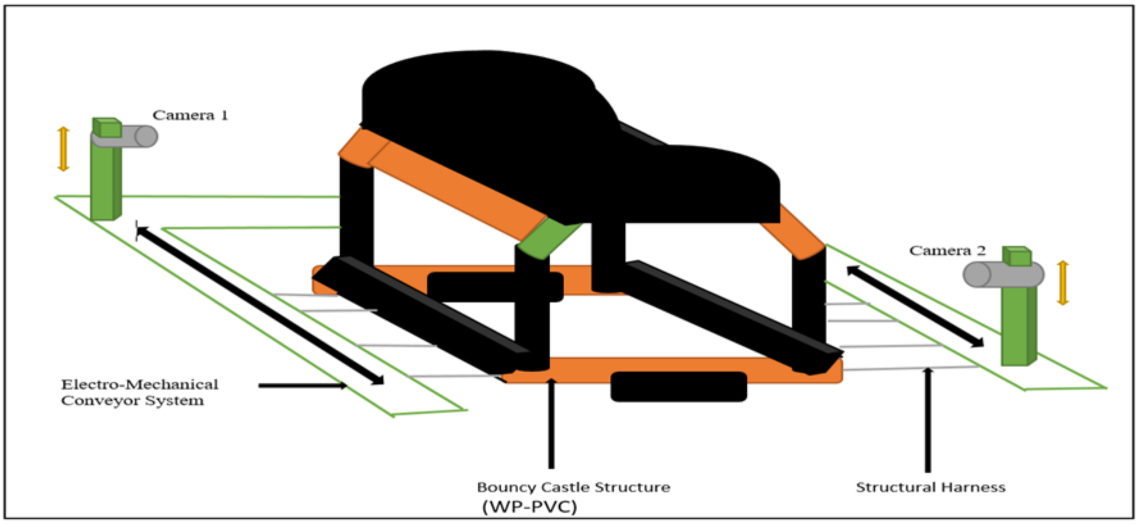

Figure 1 Conceptual design drawing of the CCS/EMCS equipment setup for fault detection of material fatigue in Bounce Castle and the surrounding periphery consisting of two infrared cameras to detect material fatigue by sliding on an electro-mechanical conveyor system with each covering 90^{o} angle of movement while in use.

Conceptual design

Camera columnar system (CCS)

An early warning and detection system comprising primarily of two infrared cameras that are positioned on each side of the Bouncy Castle is proposed. These cameras will be mounted on a columnar actuating structure allowing also for vertical movement as depicted by the yellow arrows and a surface sliding motion on a rail conveyor like system at 90^{o} motion in opposite direction for any given time depicted by the black arrows between the green bordered lines in Figure 1 above. Infrared cameras are currently widely used for non-destructive industrial material testing an example of this kind of camera is the 4100 Exo-Scan Series from Agilent Technologies and developed in partnership with Delaware University (13). The principle of operation of this equipment is Fourier Transform infrared spectroscopy (FTIR) mentioned earlier as studies conducted by (14-15) which operates based on the absorption of infrared (IR) light by a material in this case PVC, thereby causing molecular vibration of the material resulting in stretching, deformation and bending of the bonds in PVC lattice (15). Furthermore, in FTIR analysis the molecules of the material under test i.e., PVC, experiences changes in dipole moments and when the vibrational frequency of the bonds in PVC is the same as that of the absorbed IR, then, the frequency spectrum is displayed and analysed.

The result from the analysis helps to confirm the strength or weakness in the PVC material. In summary, FTIR spectrometer utilises the infrared region of the electromagnetic spectrum, from which a molecular fingerprint is obtained through the absorption of IR light by the bonds of a vibrating molecule in the material (15-21).

Electro-mechanical conveyor system (EMCS)

For this conceptual design, a Programmable Logic Controller (PLC) circuit will be used to install the above-mentioned camera columnar system on a conveyor system with separate DC sources powering the two systems. A PLC is a particularly designed computerised device that controls and operates processes and machinery by employing memory to carry out some action or function by applying stored instructions from a PLC ladder network (21-23). A PLC can perform a variety of tasks, such as timing, sequencing, counting, and data management. When the two CCS make a 90^{o} movement in opposing directions, we propose to have a sophisticated motion control with a proximity sensor/switch for this design. Using a simple PLC conveyor motor ladder logic system, the CCS is moved along a rail-like conveyor system when the start button is depressed, as shown by a green on light indicating the RUN function. A proximity sensor detects when each CCS reaches the desired 90o location around the Bouncy Castle and STOP momentarily for about few seconds indicated by a red light (23). After the time lapse, the sequence is repeated continuously of which the camera scans the Bouncy Castle horizontally and vertically with IR to detect material failure. An emergency push button will be incorporated in the system to stop the motor at any time. EMCS with CCS mounted is depicted in Fig 3 below.

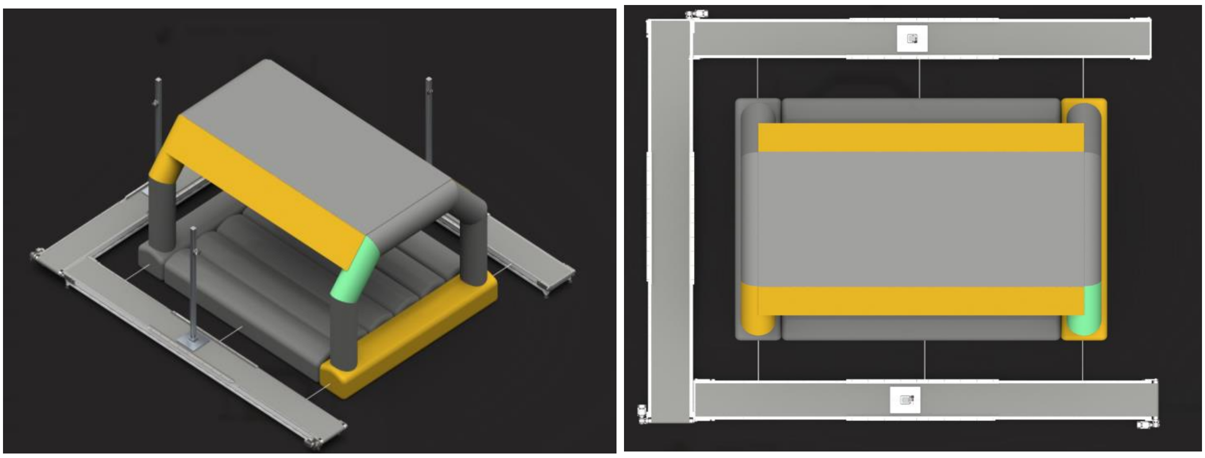

Figure 2 Depicts a conceptual design setup in 3-D solid works and top view of the fault detection system of material fatigue in Bounce castle made of PVC and the surrounding periphery consisting of two infrared cameras covering 90^{o} angle of movement to detect material fatigue by sliding an electro-mechanical conveyor system whilst in use on left and right respectively.

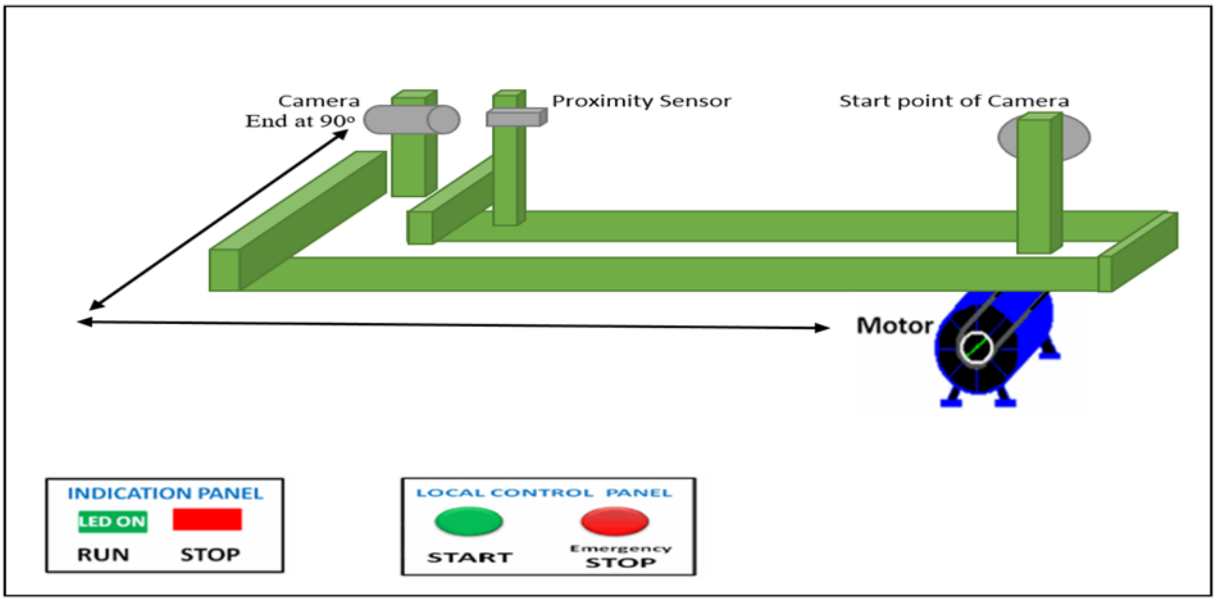

Figure 3 A pictorial diagram of an electro-mechanical conveyor system that is powered by two independent DC sources and controlled by a PLC Conveyor Motor Ladder Logic Controller and a mounted Camera Columnar System under permission to use (23).

The corresponding Rung diagram of the simple PLC Conveyor Motor Ladder Logic Controller is shown Figure 4.

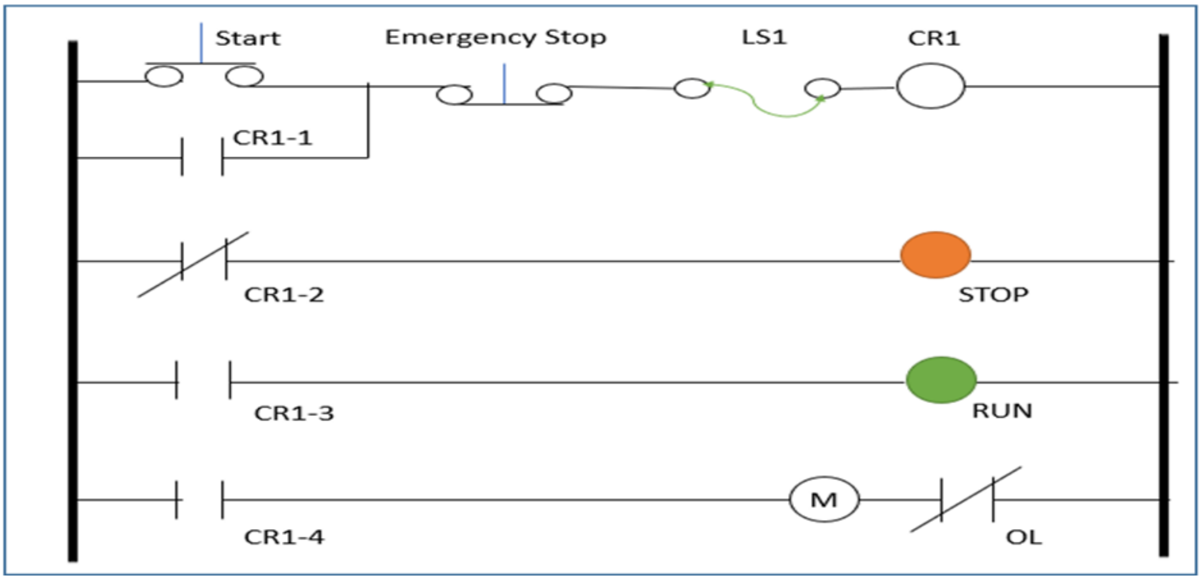

Figure 4 Rung circuit diagram of a PLC Conveyor Motor Ladder Logic Controller used for Electro-Mechanical Conveyor System (EMCS) under permission to use (23)

Expected result

The FTIR spectrum of pure PVC shown in Figures 5 displays the characteristic peaks according to investigation by (21) and (24). The spectrum comprises of vibrational peaks comprising OH stretching band at 3669cm^{-1}, CH asymmetric stretching bonds at 2971cm^{-1}. Furthermore, at vibrational peaks of 2850cm^{-1}, 1772cm^{-1}, 1426cm^{-1} are representative of long alkyl chain, C=O and CH deformation respectively with CH2 deformation bond at 1332cm^{-1} and C-CL bond stretching at 693cm^{-1} (21). Any distortion in the spectrum over time is signaled in the CCS/EMCS equipment with a buzzing sound, which may be an indication of fatigue and material weakness in the PVC.

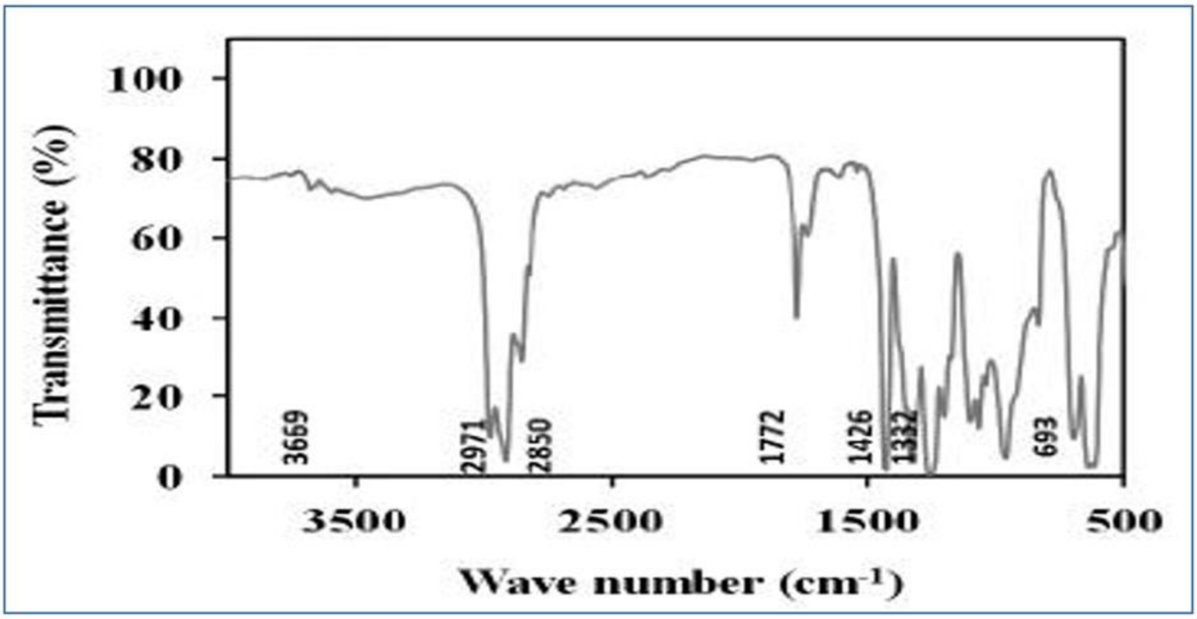

Figure 5 FTIR spectrum of pure PVC showing its vibrational bonds. With permission to use (21).

With the objective to confirm and verify the vibrational bindings of pure PVC depicted in Figure 1 above, we conducted a series of stress tests experiments on strips of new PVC material used for bouncy castle applications under varied temperature circumstances, as shown in figure 6 below.

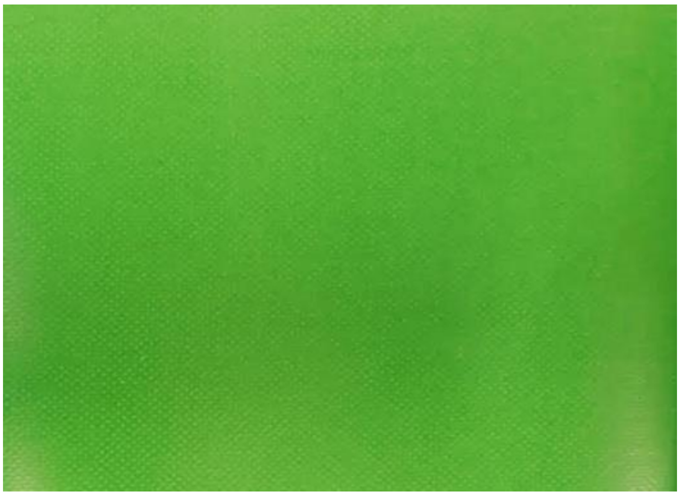

Figure. 6 shows a piece of pure PVC material that is utilised in the construction of bouncy castles.

These tests were undertaken in order to confirm and verify the vibrational bonds of pure PVC. These strips have height (H) of 13 centimeters so that they can be inserted into the jaws of the stress testing apparatus. The width (W) is 2.5 centimeters, while the thickness (d) is 0.046 centimeters. As a result of this, we are able to calculate the area (A) of the strip, which is a geometric shape that has two dimensions (25), using the mathematical expression that is displayed in Equation1 below, which is $32.5cm^2$ or $0.0325m^2$.

$$A=W\times H \quad [1]$$

The necessary stress tests on the pure PVC strips were performed with the assistance of the tensile stress test machine H25KS made by Hounsfield Test Equipment Limited (26), which is illustrated in the following Figure 7. These tests were carried out in accordance with the requirements.

Figure 7 depicts the tensile stress test machine H25KS manufactured by Hounsfield Test Equipment Limited in order to carry out the stress test on the pure PVC material that was intended for use in bouncy castles.

From the stress test, we are able to measure the force vs extension to determine the breaking point of the pure PVC material from graphs shown later in this work. Thus, the breaking point force is noted and used to ascertain the pressure the material can withstand as force per unit area relationship at the varying temperatures. The mathematical relationship (27) is seen in Equation 2.

$$\text{Pressure (P)} = \frac{\text{Force}}{\text{Area}} \quad [2]$$

In addition to that, we made use of an RS-PRO Fan Heater that had a rated power of 2000W and three different temperature settings (28), as can also be shown in Figure 8. As a result of this, we were able to simulate the influence that the temperature of the environment around us had. Furthermore, we recorded temperature measuring using the RS-PRO RS14 digital multimeter seen also in Figure 8.

Figure 8 showing on the left the RS-PRO 1000W/2000W fan heater having three temperature settings and on the right is the RS-PRO RS14 digital multimeter with a temperature sensor to measure the temperature respectively.

Firstly, we measure the FTIR spectra of pure PVC material when it was not subjected to any stress test at room temperature of 24°C as seen in Figure 9 and discovered an agreement with the FTIR spectra in the vibrational bonds extracted from lieterature in Figure 5 above.

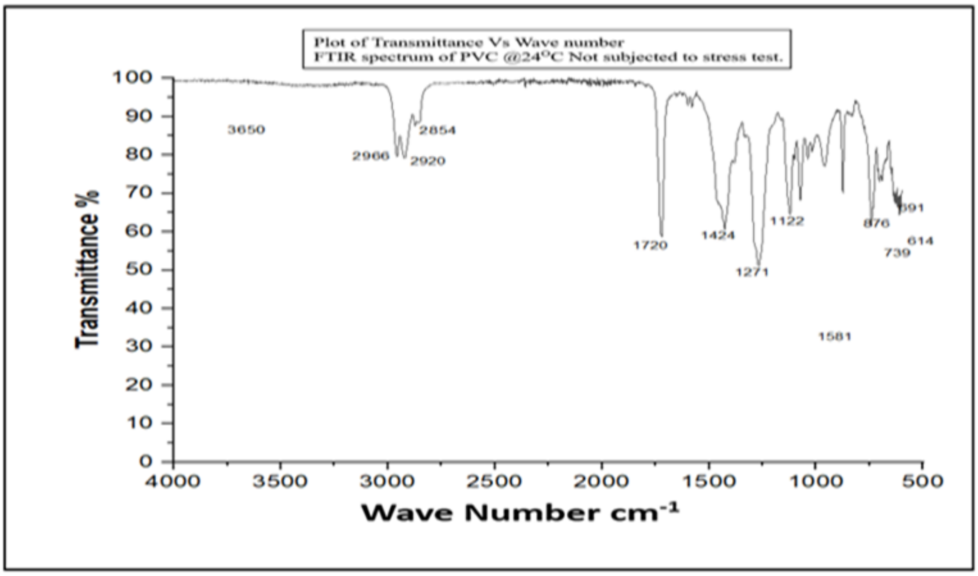

Figure 9 shows the FTIR spectra of pure PVC at room temperature with some vibrational bonds in agreement with Fig 5 extracted from literature (21).

The FTIR images and spectra was obtained using the Bruker Alpha FTIR instrument seen in Figure 10. All the generated data obtained from scanning with Infra Red (IR) were collected in the mid IR wavenumber range (500-4000cm^{-1}), at step intervals of 2cm-1 in Attenuated Transmittance Mode (ATR). This mode makes use of the transitions that occur when a wholly internally reflected infrared beam, also known as an evanescent wave, comes into contact with a sample. The evanescent waves are attenuated in the range of frequencies of infrared radiation having wavenumber between the range of (500-4000cm^{-1}), and they are absorbed by pure PVC strips. There, they go through many internal reflections before emerging from the opposite end of the sample, which is where the detector is located

(15). An interferogram is recorded by the detector, and this recording is later transformed into a frequency response. The following benefits are also available while operating in the ATR mode of FTIR: The material can be sampled much more quickly, A higher degree of reproducibility and reduced the amount of time spent preparing samples.

Figure 10 depicts the FTIR instrument Alpha Bruker. The FTIR measurements of each pure PVC samples at different temperatures were carried out with the assistance of this equipment.

Secondly, to determine the point at which each strip of pure PVC snaps to reflect the material failure and the effect of environmental temperature simulated using the RS-PRO fan heater unit, we attached each strip of pure PVC to the H25K stress tester equipment to mimic the pressure on the bouncy castle at varying temperature ranges shown on the left in Figures 11-14. The experimental set-up enabled us to establish the point at which each strip of pure PVC failed and reflected the material failure at certain environmental temperature. Additionally, this allowed us to quantify the effect of environmental temperature and pressure on the material integrity. Thus, we were able to determine the precise moment at which each strip of pure PVC ceased to properly reflect its original material property. Figures 11-14 show the experimental setup, together with the FTIR spectra that were acquired for each sample.

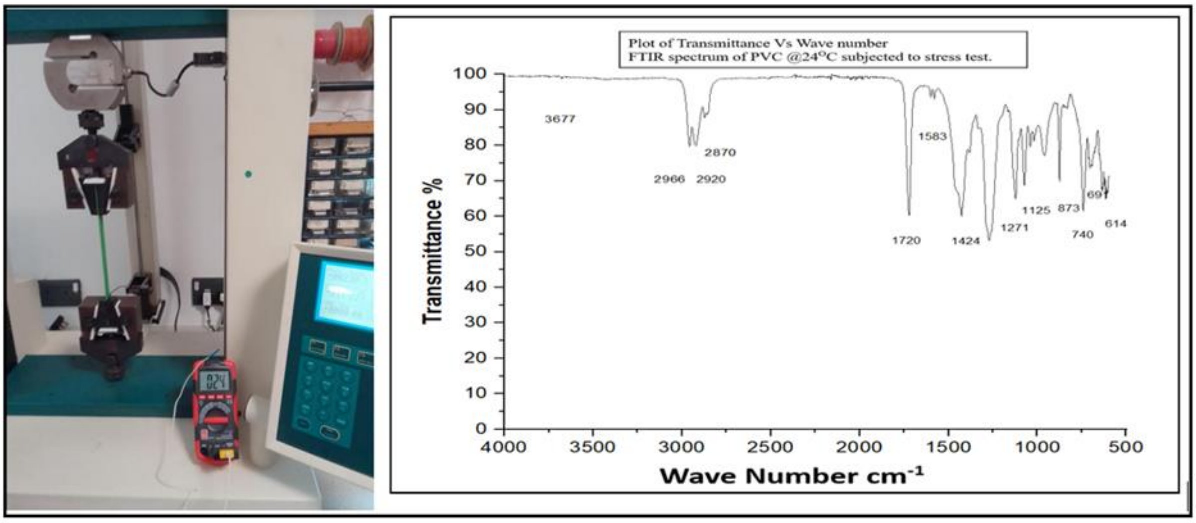

Figure 11 showing the experimental set-up for H25KS stress test on pure PVC material used for bouncy castle applications at 24oC temperature reading room temperature on the left with the corresponding FTIR spectrum showing the vibrational bonds on the right.

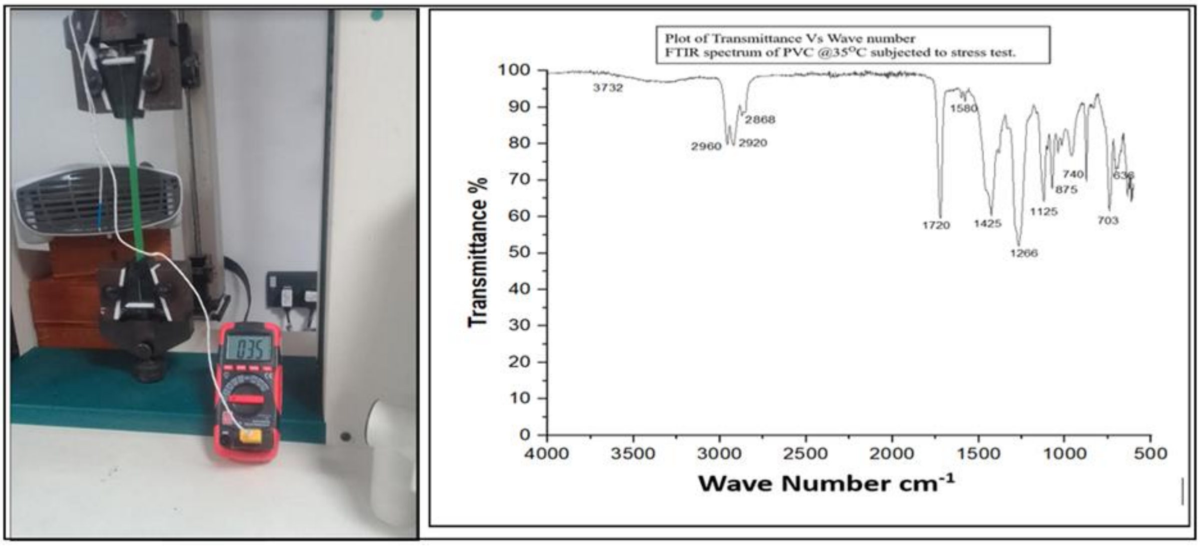

Figure 12 showing the experimental set-up for H25KS stress test on pure PVC material used for bouncy castle applications at 35^{o}C temperature reading room temperature on the left with the corresponding FTIR spectrum showing the vibrational bonds on the right.

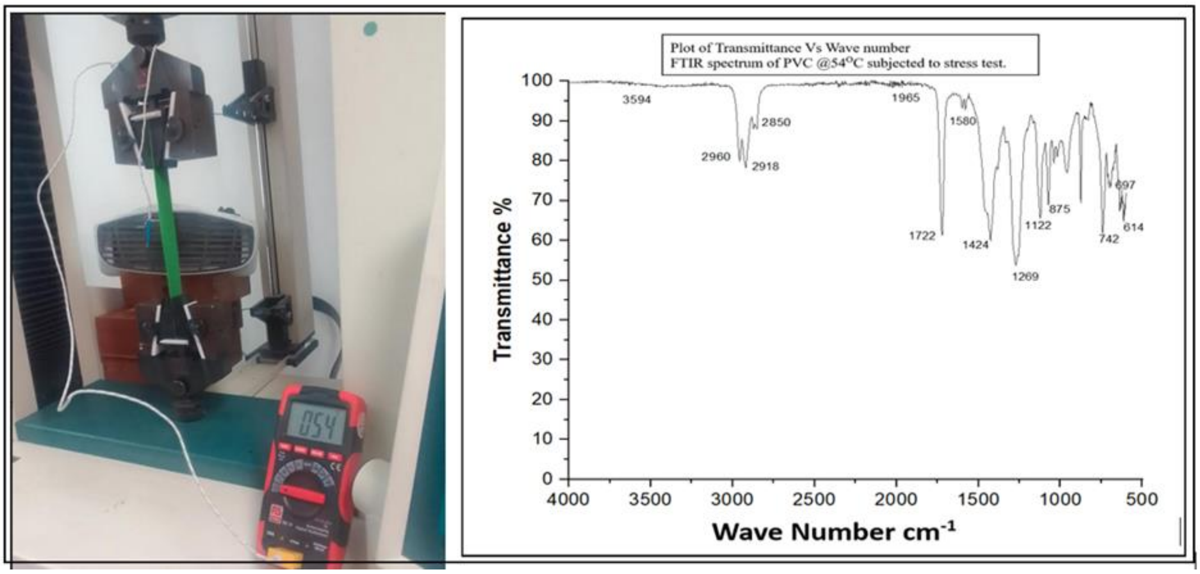

Figure 13 showing the experimental set-up for H25KS stress test on pure PVC material used for bouncy castle applications at 54oC temperature reading room temperature on the left with the corresponding FTIR spectrum showing the vibrational bonds on the right

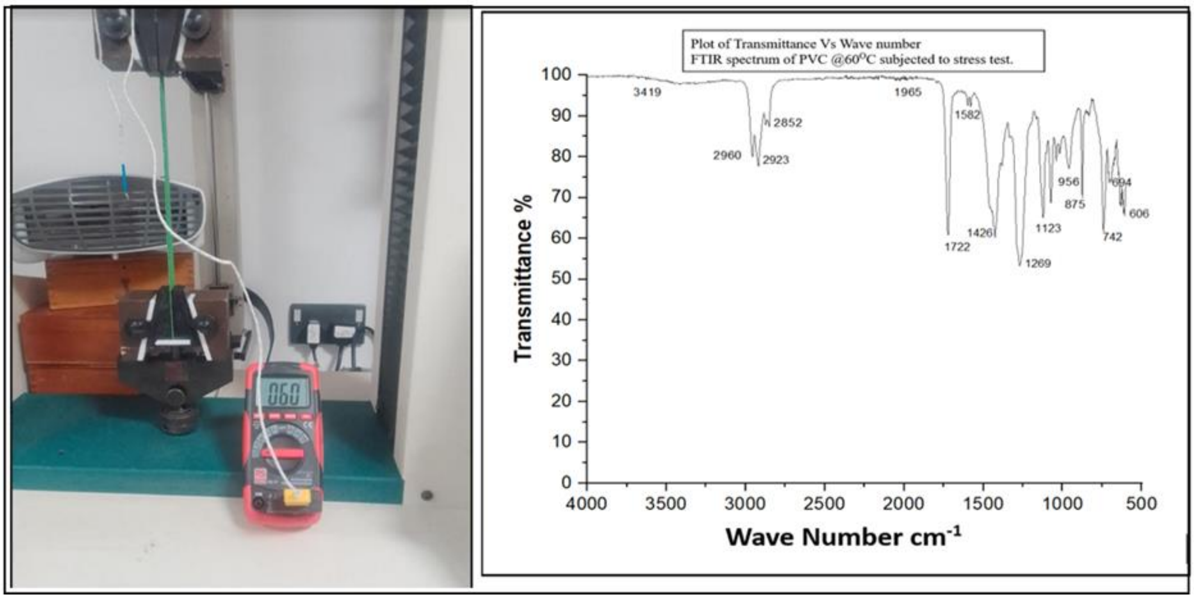

Figure 14 showing the experimental set-up for H25KS stress test on pure PVC material used for bouncy castle applications at 60^{o}C temperature reading room temperature on the left with the corresponding FTIR spectrum showing the vibrational bonds on the right.

Based on the FTIR spectra obtained from Figures 11-14 above, we observed that for all temperature there appears to be noticeable changes in the OH stretching bonds from 3669cm^{-1} when compared to what is observed in literature (21). This we attributed to the effects of temperature changes from the fan heater due to attained instability in the material. Furthermore, we suspect the pressure exerted by the tensile stress tester on the mechanical property based on time-dependent isobaric segments which connects the stress or strain, with the time-dependent response, taking the form of increased strain or decreasing and stress and vice versa in the pure PVC material (29).

On the other hand, no significant changes was observed in the Alkyl chains at C=O and the C-CL vibrational peaks for all strips tested. We conclude that this may be due to the newness of material we used for conducting the experiments. The H25KS was pre-set with an extension interval of 0.5mm at a stretching speed 1 at 2mm per minute in order to obtain many data points. See image of initial settings in Figure 15.

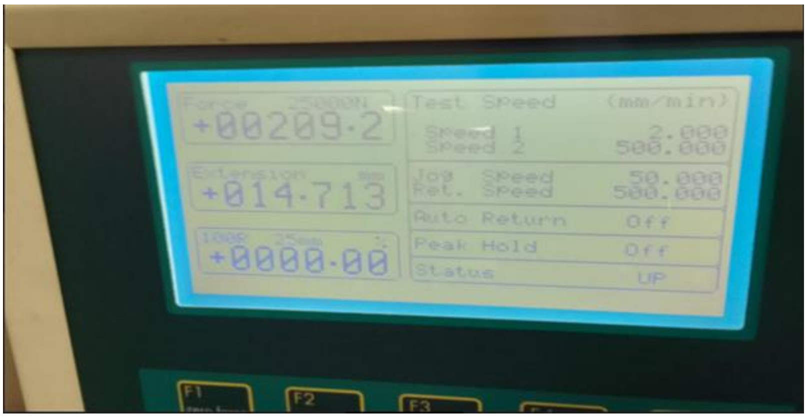

Figure 15 displays the typical liquid crystal display LCD screen of the H25KS tensile stress equipment settings.

It worth mentioning that we captured the data manually from the H25KS stress tester as the interface cable to the data capture system was faulty. As such, we acknowledge some margin of error in data capture may have arisen due to human error. When we plotted the force against the extension of each strip of pure PVC material. It was discovered that as the temperature from the fan heater increased, the time the strip snapped was shorten. The graphs of force vs extension of each sample is displayed in Figure 16-19.

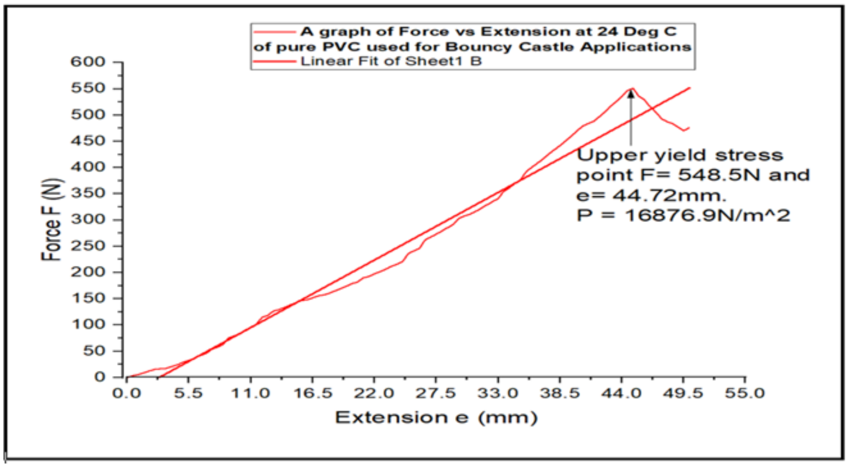

Figure 16 A graph of force vs extension in pure PVC under tensile stress test at 24°C recorded a pressure of 16876.9N/m^2. The linear fit is applied with a $R^2 = 0.98$

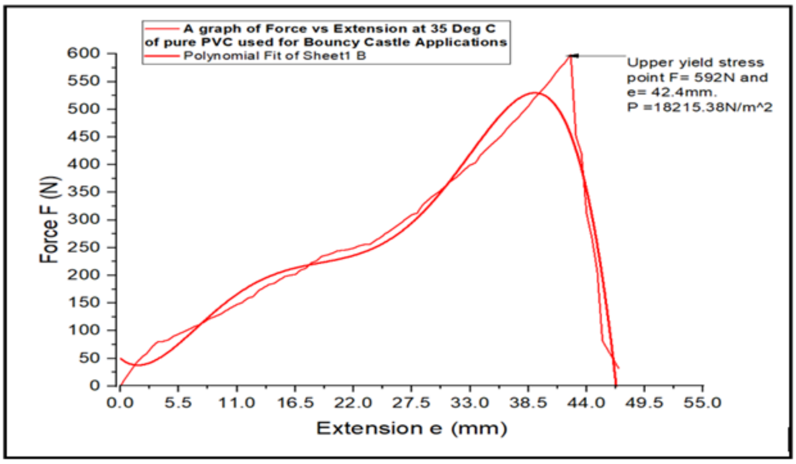

Figure 17 A graph of force vs extension in pure PVC under tensile stress test at 35°C recorded a pressure of 18215.38N/m^2. The polynomial fit is applied with a $R^2 = 0.95$

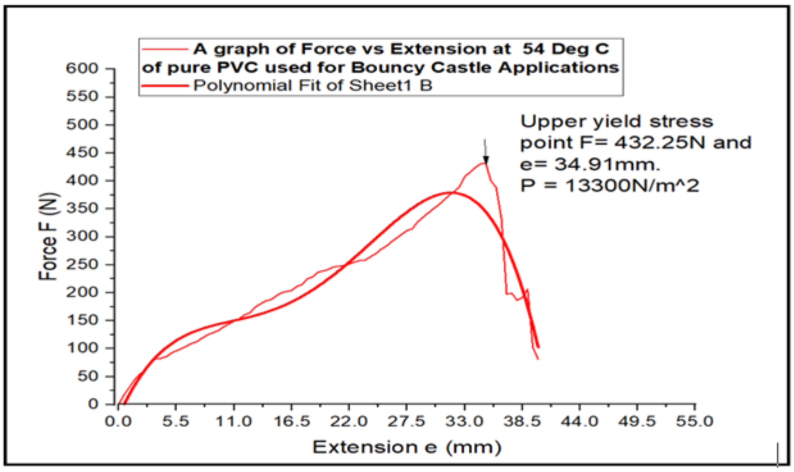

Figure 18 A graph of force vs extension in pure PVC under tensile stress test at 54°C recorded a pressure of 13300N/m^2. The polynomial fit is applied with a $R^2 = 0.92$

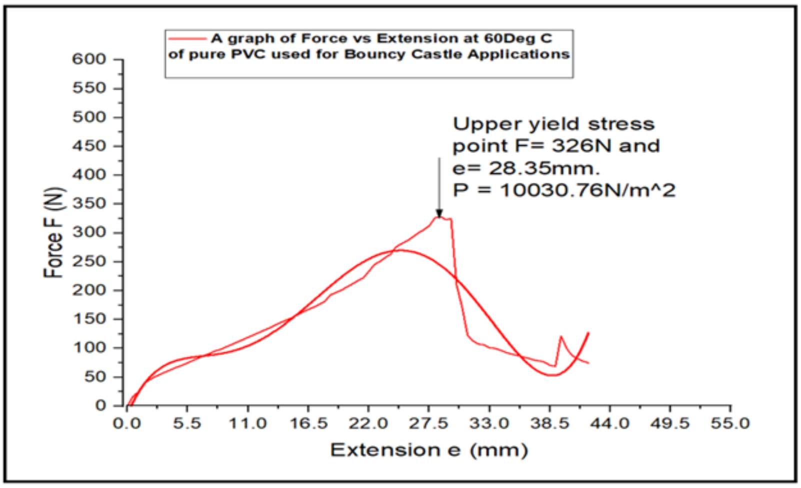

Figure 19 A graph of force vs extension in pure PVC under tensile stress test at 60°C recorded a pressure of 10030.76N/m^2. The polynomial fit is applied with a $R^2 = 0.86$

Discussion of graphical results

At a temperature of 24^{o}C, the graphs of force versus extension reveal a pattern of nearly linear behaviour on the part of the material. This may be seen in the data. This was something that we were expecting because we do not feel that this temperature is high enough to negatively affect and produce a distortion in the mechanical property of pure PVC. Additionally, the temperature at which the longest extension was measured was the same as the temperature at which the material took the longest time to break. The performance of the pure PVC material at temperatures of 35^{o}C, 5 ^{o}C, and 60^{o}C revealed vibrations within the pure PVC material as a response to the temperature and stress exerted on each sample. We hypothesised that these vibrations as depicted by the polynomial fit curves with decreasing regression R^2 value may be connected to deformation in mechanical property of the pure PVC material. In addition to this, as the temperature increased the duration it took for each strip to snap decreased. This, we reasoned, may have been caused by the beginning of the synthesis of polyenes having double $C = C$ bonds, which resulted in an unstable structure in the pure PVC material, as researched in the literature and discussed in section 1 of this article. We found that the pressure measured at the upper yield point dropped as the temperature increased. As a result of the combination of stress, strain, and temperature changes, this appears to point to the onset of slow deformation in the vibrational bonds that are contained inside the pure PVC material.

Conclusion

Due to the fatigue, stress, strain and material degradation of the PVC fabric, children who play on Bouncy Castles run a significant risk of injury, especially during the summer months when temperatures are high and lack of proper testing certification from vendors. We suggest that accidents can be decreased by utilising an equipment spectrometer infrared camera columnar system that slides around the periphery of the Bouncy Castles on an electro-mechanical conveyor system programmed controller to identify material breakdown quickly and early. We acknowledge that this conceptual design has limitations and cannot be used for all sorts of Bouncy Castle designs, but we still think it is possible to adapt the EMCS/CCS system to different Bouncy Castle structures.

Acknowledgement

We thank Samuel Warren a design technician, at Cross Manufacturing Company for the 3D design using solid works software. Furthermore, our appreciation also is extended to Engr Joe Rifai of University of West England Bristol, who helped to run the FTIR on each sample strip.

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