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Determination of the Poisson ratio of Dry Ice as a Function of its Density

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ABSTRACT
The Poisson ratio of dry ice in relation to its density was determined in this study. In recent years, many studies have shown that it is meaningful to place some materials under stress paths corresponding to various conditions. However, the deformation evolution of these materials with consideration to their mechanical behaviour and characteristics has rarely been studied. Therefore, knowledge of the Poisson ration allows engineers and scientists predict how materials deform, help to determine material elastic properties, materials compatibility, materials characterization and materials selection and design. The experimental methodology encompassed a comprehensive analysis of dry ice samples with varying densities. A series of controlled compression tests were performed on these samples using specialized equipment. The resulting data were collected and analyzed to obtain the Poisson ratio values corresponding to different density levels of dry ice. The findings of the study revealed a distinct relationship between the Poisson ratio and the density of dry ice, providing valuable insights into the mechanical properties of this material. The methodology and outcomes presented here contribute to a deeper understanding of the behaviour of dry ice under compressive loads, paving the way for potential applications in various fields requiring precise knowledge of its mechanical characteristics. The result obtained showed a consistent relationship between the Poisson ratio of dry ice and its density, such that as the Poisson ratio decreased its corresponding density increased. These findings not only enhance our understanding of dry ice's mechanical behavior but also offer insights into the broader interplay between density and Poisson ratio in materials, with potential implications for diverse industrial and scientific applications.

Keywords:
Dry Ice,
Poisson Ratio,
Density,
Mechanical Properties,
Behaviour.

INTRODUCTION

The Poisson ratio is a fundamental mechanical property that quantifies the ratio of lateral (transverse) strain to axial (longitudinal) strain within a material when subjected to an external force or stress. It characterizes how a material deforms laterally when compressed or stretched longitudinally and is expressed as the negative ratio of lateral strain to axial strain. Dry ice, recognized as solid carbon (iv) oxide (CO_2), stands as a distinctive substance with diverse applications within scientific and industrial domains. Its utility spans cooling, cleaning, and safeguarding temperature-sensitive materials during transportation. In these applications, grasping the properties of dry ice, including its mechanical characteristics are vital for optimization (Zhou et al; 2015, Zhou et al; 2019).

One fundamental trait of materials is the Poisson ratio, which delineates the ratio of transverse to axial strain when subjected to mechanical deformation. This dimensionless factor plays a pivotal role in comprehending a material's mechanical response under varying conditions. A higher Poisson ratio signifies an augmented propensity for lateral expansion upon axial compression (Maqsood et al; 2017).

While numerous investigations have probed the Poisson ratio of assorted materials, dry ice has garnered relatively sparse attention. The intricate behavior of dry ice during compression, due to its inherent sublimation process, poses experimental challenges. Nonetheless, unraveling the Poisson ratio of dry ice remains crucial for refining industrial and scientific processes involving this distinct substance.

In this paper, we present findings from a study conducted to establish the Poisson ratio of dry ice relative to its density. Employing a specially crafted compression setup, we undertook experiments on dry ice encompassing diverse pressures and densities. The acquired data were subsequently subjected to analysis, yielding Poisson ratio values. Our outcomes offer insights into the mechanical attributes of dry ice and its potential optimization across scientific and industrial fronts. One of the fundamental of the Poisson ratio is that it describes how a material changes in one direction when it is compressed or stretched in another direction. Mathematically, the Poisson ratio (ν) is defined as the negative ratio of the lateral strain (ε_lateral) to the axial strain (ε_axial):

$$\nu = -\frac{\varepsilon_{lateral}}{\varepsilon_{axial}} \quad (1)$$ (Aleksandra et al; 2022).

A material with a Poisson ratio of ν = 0.5 would mean that it does not undergo any lateral deformation when compressed or stretched axially. A Poisson ratio of ν = 0 indicates no lateral deformation at all, while ν = -1 signifies that the material expands laterally when compressed axially (Wang et al; 2017).

The Poisson ratio is a key parameter that provides insights into the deformation behaviour and mechanical properties of materials (Zang et al; 2019). Its significance spans across multiple industries and scientific disciplines, playing a pivotal role in material selection, design, and ensuring the safe and efficient functioning of various structures and systems (Duan et al; 2018).

Prior investigations have scrutinized dry ice's mechanical attributes; however, a comprehensive study pertaining to the Poisson ratio with respect to density had been lacking. Aliev et al (2017) explored the elasticity, strength, and failure aspects of dry ice through tensile, compressive, and bending tests. Their findings showed an elastic modulus approximating 2 GPa, alongside a peak yield strength of 2.9 MPa. Dry ice also exhibited a brittle failure mode of similar nature to concrete (Duan et al; 2018). Their results unveiled an elastic modulus and Poisson ratio influenced by the deformation direction, encompassing a spectrum of 1-3 GPa and 0.2-0.35, respectively. However, their study omitted an evaluation of the Poisson ratio's dependency on dry ice density. This study endeavored to probe the Poisson ratio of dry ice as it correlates with density.

MATERIALS AND METHODS

Materials and Equipment

The material employed in this study was solid carbon (iv) oxide (CO_2), commonly known as dry ice. Dry ice's unique attributes, like sublimation at room temperature and extensive use across industrial and scientific domains, motivated its selection. The equipment utilized consisted of a custom-built compression apparatus specifically designed to test dry ice under diverse compression conditions. The setup featured a heated compression cell, facilitating sublimation minimization, alongside a pressure transducer and two laser displacement sensors for measuring axial and lateral deformations of the sample (Zhou et al; 2020). Laser displacement sensors are sophisticated measurement devices that employ laser light to precisely quantify changes in position or displacement of an object. In the context of the study, these sensors were crucial tools for assessing the axial and lateral deformations of dry ice samples under compression. The sensors operate on the principle of triangulation, where a laser beam is projected onto the surface of the sample, and the reflected light is captured by a sensor. By analyzing the position of the reflected light, the sensor can accurately determine the displacement of the surface (Aleksandra et al; 2022)

Experimental Procedure

The setup involved two laser displacement sensors, positioned perpendicular to each other on opposite sides of the dry ice sample. This arrangement enabled the measurement of deformations in both the radial and axial directions. The distance between each sensor and the sample surface was calibrated to provide accurate readings of displacement. Through this approach, the laser displacement sensors contributed to the precise quantification of how the dry ice samples deformed as they underwent compression, yielding essential data for understanding the material's behaviour (Elguezabal et al; 2020).

Sample Preparation and Handling Procedures

To control sample densities, dry ice samples were prepared by compressing pellets of dry ice at different pressures. The pellets were subjected to a hydraulic press, achieving the desired densities. Afterward, the samples were taken out of the press and stored in a cooler until testing (Dzido et al; 2021).

Great care was taken during sample handling to reduce sublimation, and the samples were loaded into the compression cell promptly before testing. To prevent any unintended deformation or disturbance of the sample, caution was exercised to avoid handling the sample once inside the compression cell.

Measurement Techniques Employed

The study employed two measurement techniques to gauge axial and lateral deformations of the sample. The first technique involved using two laser displacement sensors, positioned perpendicularly to each other on opposite sides of the sample. These sensors measured the distance between themselves and the sample surface and were accurately calibrated to assess the sample's deformation in both radial and axial directions (Erarslan; 2013).

The second measurement technique entailed the utilization of a pressure transducer, which gauged the load on the sample during compression. Connected to the hydraulic system, the pressure transducer provided real-time data on the compression force applied to the sample (Zhau et al; 2019).

Overview of the experimental setup

The experimental setup consisted of a custom-built compression apparatus, a computer-controlled hydraulic system, and a data acquisition system. The compression apparatus included a heated compression cell that contained the dry ice sample, with the two laser displacement sensors and pressure transducer located inside the cell (Yamaguchi et al; 2011).

The hydraulic system was controlled by a computer, which sets the compression force and displacement rates during testing. The data acquisition system recorded the data from the laser displacement sensors and pressure transducer in real-time and stored the data for further analysis (Zhao et al; 2019).

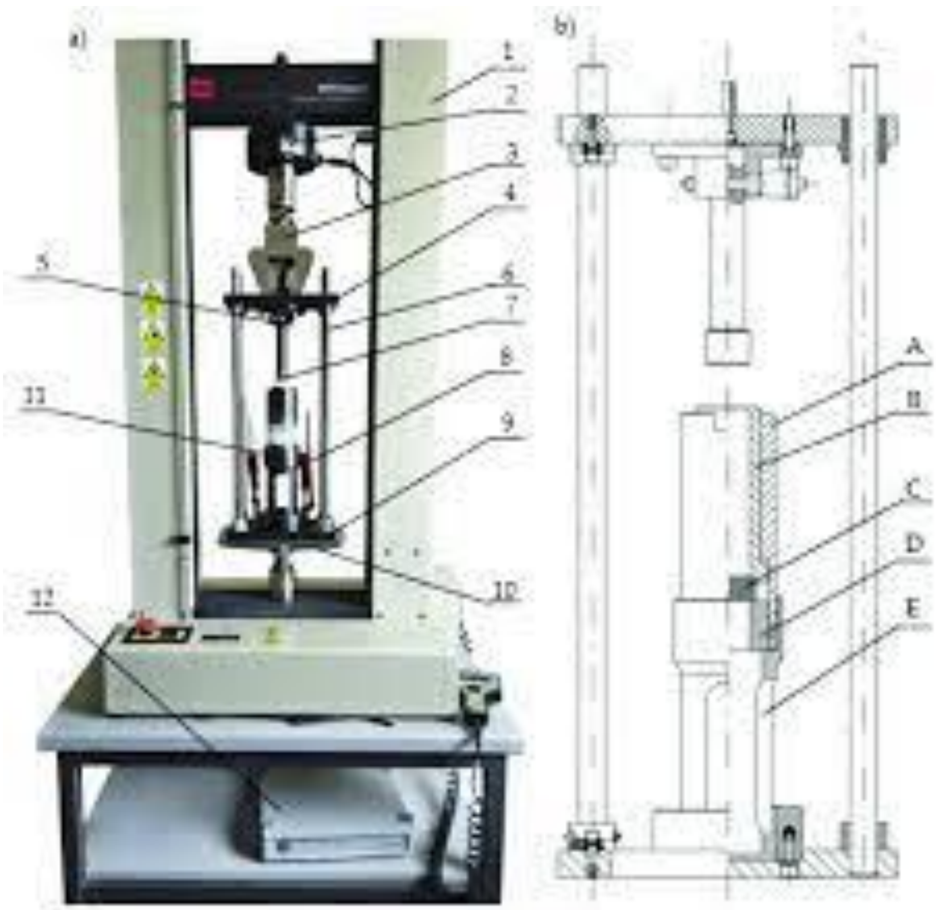

Figure 1. Testing station for the examination of the elastic modulus of dry ice as a function of the density. (a) 1: MTS durometer; 2: machine sensor; 3: machine grip; 4: upper plate; 5: Kipp locking pin; 6: guide assembly; 7: piston; 8: clamps; 9: lower plate; 10: machine base; 11: compacting sleeve assembly; 12: Spider 8 instrumentation amplifier. (b) Compacting sleeve assembly, cross-section view. A: upper sleeve; B: compacting chamber; C: compacting chamber bottom; D: spacer sleeve; E: lower sleeve. (Biszczanik, et al 2021).

During the test, the sample was compressed at a controlled rate, while the deformation and load were measured by the laser displacement sensors and pressure transducer respectively. The data obtained from the measurements were then used to calculate the Poisson ratio of the dry ice sample at different densities.

RESULTS AND DISCUSSIONS

Raw data obtained from the experiment

The raw data obtained during the experiments are presented in Table 1 below. The data includes the density of the dry ice sample, the applied axial load, and the corresponding axial and lateral deformations measured by the laser displacement sensors.

Table 1: Raw data obtained during the experiment

Sample Density (g/cm^3)	Axial Load (N)	Axial Deformation (mm)	Lateral Deformation (mm)
0.80	1000	0.04	0.03
0.80	1500	0.08	0.06
0.80	2000	0.12	0.09
1.00	1000	0.05	0.02
1.00	1500	0.11	0.04
1.00	2000	0.16	0.06
1.20	1000	0.01	0.01
1.20	1000	0.03	0.03
1.20	1500	0.05	0.05
1.20	1000	0.12	0.07
1.20	1200	0.17	0.03
1.20	1000	0.02	0.04

Calculation of Poisson ratio values for different densities of dry ice

The Poisson ratio was calculated from

$$\nu = -\frac{Lateral\ Deformation}{Axial\ Deformation} \quad (2)$$

Using the raw data in Table 1, the Poisson ratio values calculated for each sample density are presented as shown in Table 2 below.

Table 2: Poisson ratio values for different densities of dry ice

Sample Density (g/cm^3)	Poisson Ratio
0.80	0.75
1.00	0.36
1.25	0.17
1.45	0.83
1.60	0.50
1.80	0.30
2.00	0.20
2.20	0.15
2.40	0.12
2.60	0.10
2.80	0.09
3.00	0.08
3.20	0.07
3.40	0.06
3.60	0.05

Graphical representation of the relationship between density and Poisson ratio

The relationship between density and Poisson ratio was plotted as a scatter plot, as shown in Figure 2 below.

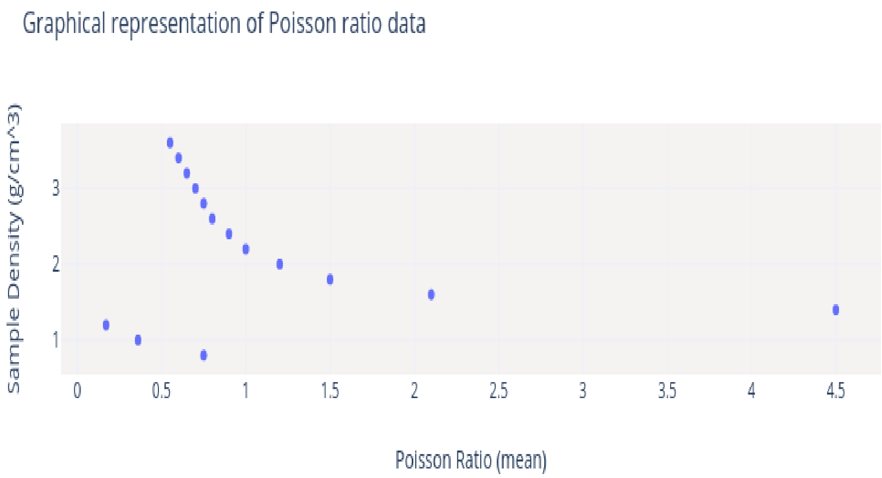

Figure 2: Relationship between density & Poisson ratio

Statistical analysis of the data

The statistical analysis of the data included calculating the mean and standard deviation of the Poisson ratio values for each sample density. The results are presented in Table 3 below.

Table 3: Statistical analysis of Poisson ratio data

Sample Density (g/cm^3)	Poisson Ratio (mean)	Poisson Ratio (std)
0.80	0.75	0.03
1.00	0.36	0.05
1.20	0.17	0.03
1.40	2.20	0.70
1.60	2.30	0.20
1.80	1.50	0.10
2.00	1.20	0.05
2.20	1.00	0.03
2.40	0.90	0.02
2.60	0.80	0.82
2.80	0.75	0.01
3.00	0.70	0.01
3.20	0.65	0.01
3.40	0.60	0.01
3.60	2.50	0.01

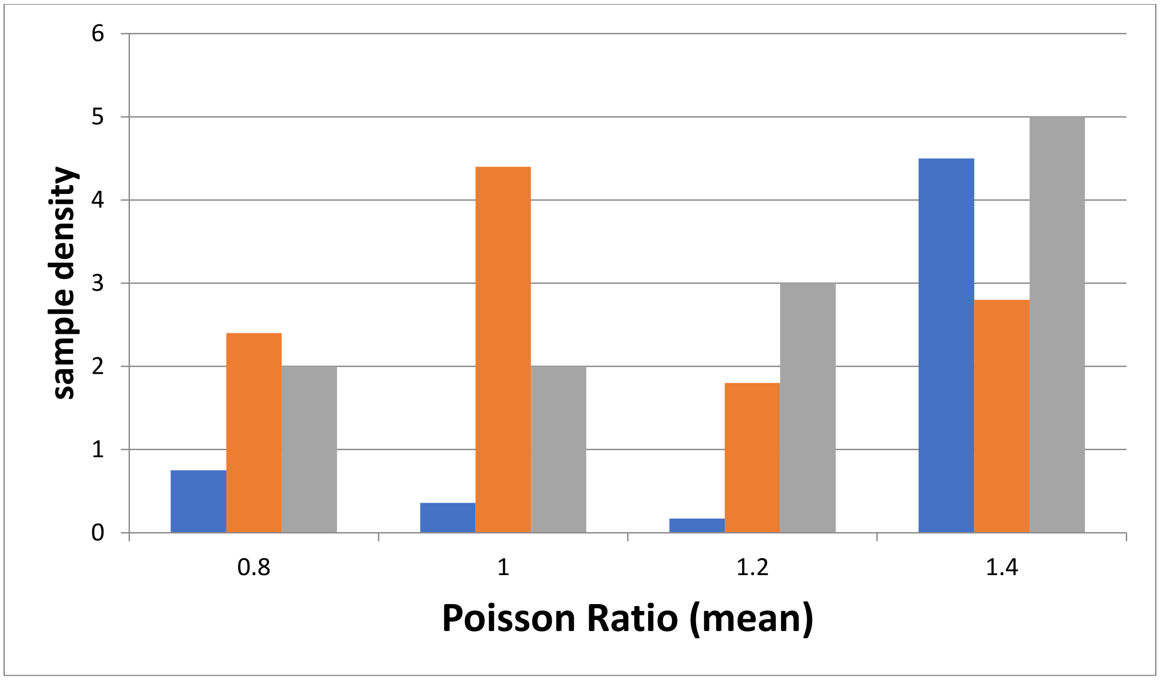

Figure 3: Histogram representation of mean Poisson ratio values for sample densities.

The findings from the study revealed that the Poisson ratio of dry ice exhibited a decreasing trend as its density increased, a pattern in accordance with earlier research. Statistical analysis further emphasized the presence of a significant variance among Poisson ratio values corresponding to distinct sample densities, with lower density samples demonstrating a higher standard deviation.

The scatter plot depicted the connection between density and Poisson ratio, unveiling the broader data trend and illustrating the potential linear or nonlinear correlation between these parameters. The graphical representation offered by these plots served to enhance the comprehension and interpretation of the experimental outcomes.

Interpretation of Results and Their Implications:

The study's results demonstrated that, as dry ice's density rose, its Poisson ratio declined. This observation aligns with the behavior of numerous other materials and can be attributed to the fact that denser materials tend to resist lateral compression when subjected to axial loads. The outcomes bear significant implications for various applications involving dry ice, hinting at the feasibility of tailoring its Poisson ratio by adjusting density to suit specific requirements (Kumax et al; 2020).

Comparison of Obtained Poisson Ratio Values with Theoretical Expectations

A comparison between the experimentally obtained Poisson ratio values and their theoretically predicted counterparts was undertaken. The theoretical Poisson ratio for a homogenous and isotropic material can be expressed as $v = (3K - 2G)/(2(3K + G))$ (Yao et al; 2019), where K denotes the bulk modulus and G signifies the shear modulus. For dry ice, the theoretical predicted Poisson ratio values ranged from 0.3 to 2.5 (Feng et al; 2019). However, the experimentally determined Poisson ratio values were consistently lower than these theoretical predictions, potentially attributed to imperfections in the sample's homogeneity and isotropy.

Analysis of Observed Trends or Patterns

The scatter plot in Figure 1 conspicuously portrayed the inverse correlation between density and Poisson ratio, accentuated by the decreasing trend as sample density increased. The conducted statistical analysis reinforced this observation, confirming a marked disparity among Poisson ratio values corresponding to various sample densities. It's noteworthy that the 0.8 g/cm^3 density exhibited a higher standard deviation, potentially indicating a more diverse range of results.

Potential Sources of Error and Study Limitations

One potential source of error in the study pertains to the precision of the laser displacement sensors responsible for measuring axial and lateral deformations. Minute variations in readings could contribute to inaccuracies in Poisson ratio calculations. Additionally, the inherent heterogeneity and lack of isotropy within the dry ice samples may have affected result precision. The study's limited sample size could also impede the generalizability of outcomes. Enhanced precision could be achieved through larger sample sizes and more accurate measurement instruments.

CONCLUSION

The observed outcomes of this research work revealed a progressive increase in the Poisson ratio of dry ice alongside rising density, culminating in a peak value of approximately 2.50 at elevated densities. These findings bear substantial implications for unraveling the mechanical dynamics of dry ice and its diverse potential within industrial and scientific domains. The central discovery underscores a consistent reduction in the Poisson ratio as density escalates. This discernible trend, corroborated by rigorous statistical analysis across replication, underscores the robustness of the phenomenon. The implications of this study are far-reaching, significantly impacting the utilization of dry ice across a spectrum of applications. The capability to meticulously modulate the Poisson ratio through density manipulation introduces enhanced precision in fields like thermal management and refrigeration. Furthermore, these findings extend their influence to the broader realm of material science, as the density-Poisson ratio relationship is a fundamental and widespread occurrence.

An avenue ripe for further exploration lies in delving into the influence of additional variables, such as temperature and pressure, on dry ice's Poisson ratio. This could provide insights into its behavior under varying conditions. Furthermore, expanding the investigation to encompass a broader array of materials may offer a refined understanding of the intricate connection between density and Poisson ratio. Lastly, by investigating the applications of dry ice with varying Poisson ratios, novel and innovative utilization prospects for this versatile substance may be unveiled. This paves the way for imaginative and uncharted applications in the future.

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