

**A FUNDAMENTAL MECHANICAL ANALYSIS OF THE TEXTURE OF
FRENCH FRIES**

A Thesis

Submitted to the Faculty

Of

Graduate Studies

The University of Manitoba

By

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In Partial Fulfillment of the
Requirements for the Degree

Of

Master of Science

Food Science Department

June 11, 1999



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A Fundamental Mechanical Analysis of the Texture of French Fries

BY

Kelly Anne Ross

**A Thesis/Practicum submitted to the Faculty of Graduate Studies of The University
of Manitoba in partial fulfillment of the requirements of the degree**

of

MASTER OF SCIENCE

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This thesis is dedicated to the loving memory of my Grandma

ACKNOWLEDGEMENTS

There are many individuals whom have helped me greatly through the preparation of this thesis. I would like to thank Dr. Martin Scanlon for advising this research, for his valuable guidance and for his unwavering support throughout this project. I would also like to thank Dr. Scanlon for inspiring me to continue on with my academic career in the pursuit of a doctoral degree. Sincere appreciation is extended to the Association of Universities and Colleges of Canada for an Agriculture and Agri-Food Canada scholarship, the Canadian Dairy and Food Industries Supply Association, and the Natural Sciences and Engineering Research Council of Canada for their financial support. I would like to thank Randy Roller for his valuable computer assistance, whenever I had a problem with my computer Randy would save the day. I would like to thank Jim Rogers for his technical assistance with the “Fig P” made graphs in this thesis. Jim kindly let me sit at his computer for extended periods of time. I am grateful to Dr. L. Malcolmson and D. Ryland, Foods and Nutrition Department, for allowing me access to the Lloyd instrument. I’m also grateful to Lorne Adam, Plant Science Department for helping with the storage of the potatoes used for this research. A sincere thank-you is extended to Dr. Jayaraman, Mechanical Engineering Department and Dr. Pritchard, Plant Science Department, for their critical review of this manuscript. I would like to thank the graduate students of Food Science for their practical and moral support of this endeavor; your smiling faces and jokes made “The Department” feel like a second home.

I would like to thank my Mom and Dad for their support over the years. I would like to thank my sister Cindy for her friendship, unlimited support, and her faith in me. I

would also like to thank her for her technical assistance. Without Cindy, there wouldn't have been any photomicrographs in this thesis. I would like to thank Brian for being like a big brother to me; your kindness is very much appreciated. I would like to thank Tammy for her unending support and friendship over the years. Finally, I would like to thank Celine (aka Masa Don) for her unlimited friendship, support and laughter. Yes my friend, good times, good times.

ABSTRACT

Texture is a major index of food quality and it is a major index of quality in food processing plants. Texture is one of the most important quality attributes of the french fry and is important for quality control in the potato processing industry. Indentation tests are frequently used in the food industry as a simple means of texture evaluation. However, indentation tests generally provide empirical results for product texture rather than fundamental results. This thesis attempted to understand how mechanical parameters characterizing the textural properties of french fries could be derived from indentation tests. The focus of the first part of this study was to obtain a fundamental mechanical parameter, the elastic modulus, of a model food system (an agar gel), from the indentation test. Cylindrical indenters with varying diameters were used as indentation probes on large slabs of a 3% agar gel. A 3% agar gel was chosen because its mechanical properties are similar to those of cold french fry interior. Compression testing, using lubricated teflon platens and a travelling microscope, was used to independently measure the gel's elastic modulus (52 kNm^{-2}) and Poisson's ratio (0.32). Indentation measurements of reaction force (P) and deformation (d) were analyzed with the theoretical relationship for frictionless flat cylinder indentation. A good linear fit ($r^2 = 0.991$) was obtained for P/d versus indenter radius, indicating the validity of the analysis. However, the value of the elastic modulus derived from indentation was 79 kNm^{-2} . The indentation derived elastic modulus overestimated the compressive elastic modulus by 52%. Such a large overestimate suggests that additional factors to those considered in the theoretical model influence the indentation process. The presence of pores in the gel, frictional forces during indentation, and elastic mismatch between

indenter and gel all may affect the indentation process. Nevertheless, similarity in results for the elastic modulus determined from indentation compared to compression, indicates that a simple testing method can yield a more comprehensive evaluation of food textural quality.

The focus of the second part of this study was to use a fundamental engineering approach to quantify the mechanical properties of the fried potato crust. The effect of frying time on the mechanical properties of fried potato crust was investigated and values for the fracture stress, fracture strain, elastic modulus, and fracture toughness of the fried potato crust were quantified. It was found that frying time had an effect on the mechanical properties of the fried potato crust. The fracture stress and elastic modulus values increased as fry time increased while the fracture strain and fracture toughness values decreased as fry time increased. The fracture stress and elastic modulus values were in the range of 100 kNm^{-2} and 1 MNm^{-2} , respectively. Fracture strain was in the range of 1-10 % strain. Fracture toughness was of the magnitude of 10 Jm^{-2} . With respect to fracture toughness, as length of fry time increased the crust material changed from a ductile or pliant material to a more brittle material. A value of the Poisson's ratio was unable to be quantitatively measured, but microscopy was employed to deduce that the value was 0.5. Therefore, it was determined that the tensile test commonly used to measure fundamental mechanical parameters of engineering materials can also be employed to characterize the texture of fried potato crusts. Thus, an accurate means of obtaining indices of french fry quality may be possible through crust property measurements.

The focus of the third part of this study was to apply a full mechanics approach to the indentation analysis of a biological composite material. A 3% agar gel was modeled as the core of the composite material and fried potato crusts of various thicknesses were modeled as the facesheets of the composite material to simulate the structure of a french fry with the aim of characterizing the indentation process. Using a theory which incorporated small plate deformation theory and plastic deformation theory, and membrane deformation theory, the load-deformation response of this biological composite material was characterized. The theoretical predictions of load-deformation response for indentation of a biological composite were in reasonable agreement with the experimental results. At indentation deformations less than half the crust thickness, the indentation process was characterized by the linear-small plate deformation theory. At indentation deformations greater than half the crust thickness but less than the total crust thickness the indentation process was characterized by non-linear plastic deformation theory. At indentation deformations greater than the total crust thickness, the indentation process was defined by the membrane theory.

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1.0 INTRODUCTION

Food texture is considered a key quality parameter in the development and acceptance of food products (Bourne, 1982; Finney, 1969). Also, much of food processing is basically directed to changing the textural properties of the foods (Bourne, 1982). Therefore texture is an important parameter of food quality and its evaluation is necessary for good quality control in a food processing plant (Finney, 1969).

Interestingly, even with the importance of texture to the food industry only a small number of food scientists have dedicated their research to food texture measurement (Bourne, 1982). Texture studies regarding sensory methods constitute a large proportion of the research that has been performed. Of the work that has been done on instrumental texture measurement, a large volume exists on empirical tests and only a small volume exists on fundamental tests (Bourne, 1994; Bourne, 1982). This is not in accordance with the findings of a survey performed by Cumming *et al.* (1971) which indicated aspiration for greater standardization and fundamental understanding of texture tests within the food industry.

Indentation is one of the most simple and widely used type of instrumental tests in the food industry (Bourne, 1982). However, the indentation test generally provides measurements of texture that are mainly empirical in nature. Yet, there are defined mechanical properties associated with inherent qualities of a food (Mohsenin, 1970). For example, the elastic modulus is a well defined fundamental mechanical property which can be used to characterize the texture parameter of tenderness (Mohsenin, 1970). In the engineering field, the indentation process has been analytically studied in order to determine the conditions whereby true values of elastic modulus can be obtained. As an

example, this approach has been used on synthetic biological materials, namely, rubber (Briscoe and Sebastian, 1993). Therefore one of the objectives of this research was to obtain the elastic modulus of a model food system (a 3% agar gel) by applying the theory of elasticity to the indentation process. The focus of the first part of this study was to obtain the elastic modulus of a model food system (an agar gel) from the indentation test.

French fries are becoming increasingly popular worldwide (Anon, 1988). In fact, Talburt *et al.* (1987a) stated that the production of frozen french fried potatoes has exceeded an annual value of one billion dollars in North America. In Manitoba, french fries account for nearly 80% of all processed potato products, and contribute up to 66 million dollars in revenue (Manitoba Agriculture, 1998). French fry quality is of paramount importance for consumer acceptability and texture is one of the three main attributes that describe french fry quality. In spite of the magnitude of potato production and its economic importance, the potato processing industry continues to have problems in the evaluation and control of french fry texture (Ross and Porter, 1971). A french fry consists of two components, the crust, which is a crisp exterior; and the core, which is a soft mealy interior (Voisey *et al.*, 1974). Another of the objectives of this research was to measure the mechanical properties of the crust of a fried potato. Mechanical properties could be used to quantify the many variables encountered in potato processing that are technologically important to the industry. Source and variety of potatoes, storage conditions and processing conditions all affect the texture of french fries (Ross and Porter, 1971). It would be beneficial if the effects of these parameters were efficiently quantified through the measurement of the mechanical properties of french fries.

A french fry consists of two components, the crust and the core (Voisey *et al.*, 1974) and it is these two components that characterize its texture. It follows that french fries can be considered to be a type of composite material since french fries consist of two principal components that differ in their textural properties and thus their mechanical properties. In the aerospace industry there has been research performed on the anisotropic elasticity encountered in composite materials such as sandwich panels (Sakamoto *et al.*, 1991). Static indentation analysis of composite sandwich panels has been studied computationally and theoretically (Frostig *et al.*, 1992; Olsson and McManus, 1996). The load history for the indentation of a composite sandwich material has been determined to consist of three regimes: linear elastic, non-linear plastic, and non-linear plastic with membrane stresses (Olsson and McManus, 1996).

The last objective of this research was to use the test methods developed in the discipline of mechanical engineering for industrial composite sandwich materials for the analysis of the mechanical behaviour of a biological composite material. It was postulated that a full mechanics analysis could be used to describe the indentation process of a biological composite material consisting of fried potato crust and an agar gel. Therefore, a fundamental evaluation of french fry texture would be feasible by performing simple indentation tests.

2.0 LITERATURE REVIEW

2.1 Importance of Texture as an Index of Quality

Much of food processing is basically directed to changing the textural properties of the foods (Bourne, 1982). Texture is an important parameter of food quality and its evaluation is necessary for quality control in a food plant (Finney, 1969). Texture is also a key parameter in the development and acceptance of food products (Bourne, 1982; Finney, 1969). A study was done by Cumming *et al.* (1971) which stated that heavy use was made of sensory tests in the food industry as methods of texture evaluation. However, of those in the food industry using sensory tests, 64% coupled their sensory methods with instrumental methods. 98.4% of the food processors that were using instrumental tests intended to continue or expand their use of instrumental tests for measuring texture. Also, it was noted that 70% of those in the food industry using instrumental tests expressed a desire for greater standardization of instrumental test methods (Cumming *et al.*, 1971). Sensory methods were considered by some food processors to be too costly and too time consumptive to be an efficient method of quality control (Voisey, 1971). Although sensory tests are ideal in that they predict what the consumer will think of the final product, instrumental tests are considered to be a more efficient method of texture evaluation (Cumming *et al.*, 1971; Voisey, 1971).

Concern has been expressed for greater uniformity of texture terms in order for results obtained from instrumental methods to be better correlated with sensory methods. Interestingly, with all of the uncertainty regarding food texture and its measurement, compounded with the importance of texture to the food industry, only a small number of

food scientists have dedicated their research to food texture measurement (Bourne, 1982; Szczesniak, 1963).

Texture studies using sensory methods make up a large proportion of the research that has been performed (Bourne, 1982). Of the work that has been done on instrumental texture measurement, a large volume of literature exists on empirical tests and only a small volume exists on fundamental tests (Bourne, 1982). Interestingly, this is in contrast to the desire of food processors to have standardization of texture tests and clarification of texture measurements (Cumming *et al.*, 1971).

2.1.1 Types of Instrumental Texture Tests

There is a wide range in types of foods and concomitantly many types of textures that foods exhibit, so there are different instrumental methods available to measure food texture (Friedman *et al.*, 1963). Therefore, it has been necessary to classify the different instrumental methods of texture evaluation to fully understand the problems involved in food texture measurement (Bourne, 1982). Two approaches, with respect to instrumental texture measurements, have been used to conduct research into the textural characteristics of the product and for production quality control. Empirical and fundamental tests are the instrumental tests used for measuring food texture (Bourne, 1994).

2.1.1.1 Empirical Tests

Empirical tests are the most widely used class of instrumental texture tests in the food industry (Bourne, 1982). “Empirical tests have been developed from practical experience as an expedient method to measure something related to texture” (Bourne,

1982). Examples of instrumental empirical tests include the shear-press, penetrometers, gelometers, viscometers, compressimeters, consistometers, and tenderometers (Freidman *et al.*, 1963). There are advantages and disadvantages associated with empirical tests.

2.1.1.1.1 The Advantages Associated with Empirical Tests

Empirical tests of food texture are very practical and easy to use (Bourne, 1994). They are inexpensive tests. Empirical tests are also very rapid in that sample preparation is quick and results can be obtained very quickly. Most importantly, empirical tests can give results that correlate well with foods' sensory properties (Bourne, 1994). For example, Ross and Porter (1966) used the shear compression cell of the Kramer Shear Press to obtain instrumental texture measurements of french fries. It was possible to note the forces at which initial failure/fracture of the outer crust and shearing of the crust layers occurred. Ross and Porter (1966) showed with shear curves the effect of frying time, and frying time along with cooling time on french fry texture. It was found that peak force increased with increased frying time. For frying time and cooling time, the peak force values were still the highest at longer fry times but the peak force was lower when cooling was allowed. This indicated that a redistribution of water had taken place (Ross and Porter, 1966).

2.1.1.1.2 The Disadvantages Associated with Empirical Tests

There are problems associated with empirical tests. There is poor definition of what is being measured by the test (Bourne, 1994). An empirical test is an arbitrary test; there is no expected correlation between results obtained from one experimenter to the next (Kamel and deMan, 1975a). This fact can be seen in Ross and Porter's (1966) french fry

texture measurements with the shear press. It was noted that the use of different sized blades would yield different force readings. The root of the problems associated with empirical tests is their lack of scientific or fundamental understanding (Bourne, 1994).

2.1.1.2 Fundamental Tests

In the field of engineering, tests used for determining the mechanical properties of industrial materials are rigorously defined and based on a solid fundamental understanding (Beer and Johnston, 1992). There are standard methods for materials testing used to obtain well-defined fundamental mechanical properties. Examples of these fundamental mechanical properties include modulus of elasticity (E), yield stress (σ_y), fracture stress (σ_f), Poisson's ratio (ν), and fracture toughness (T) (Bourne *et al.*, 1966; Dobraszczyk, 1994; Mohsenin, 1970).

2.1.1.2.1 Modulus of Elasticity

The modulus of elasticity (E) is the proportionality constant, at small deformations, that relates stress and strain, which is given by the following equation (Beer and Johnston, 1992).

$$E = \sigma/\epsilon \quad (1)$$

Where: σ is the stress, which more explicitly is the applied force divided by the area perpendicular to the applied force; ϵ is the strain, a measure of deformation caused by stress, or the change in length of the sample divided by the original length of the sample.

2.1.1.2.2 Yield Stress and Fracture Stress

Yield Stress (σ_y) is the stress value at which yielding occurs, and is given by the following equation (Beer and Johnston, 1992).

$$\sigma_y = F_{\perp}/A \quad (2)$$

Where: F_{\perp} is the applied force divided by the area (A) perpendicular to the applied force.

Ductile materials are characterized by their ability to yield at normal temperatures. As a specimen that exhibits ductile properties is subjected to increasing force, its length will increase linearly at a slow rate. However, when a critical stress is reached, the specimen undergoes large failure with a small increase in applied load. This critical stress value is the yield stress (Beer and Johnston, 1992).

Fracture Stress (σ_f) is the stress value at which fracture occurs, and is given by the following equation (Beer and Johnston, 1992).

$$\sigma_f = F_{\perp}/A \quad (3)$$

Where: F_{\perp} is the applied force divided by the area (A) perpendicular to the applied force.

Fracture involves the failure or cracking of a material (Vincent, 1990). Typically, fracture is the mode of failure for a brittle material. Fracture is characterized by the fact that failure occurs without any noticeable prior change in rate of elongation (Beer and Johnston, 1992).

2.1.1.2.3 Poisson's Ratio

Poisson's ratio (ν) is the ratio of lateral strain to axial strain, which is given by the following equation (Beer and Johnston, 1992).

$$\nu = -\epsilon_l / \epsilon_a \quad (4)$$

Where: ϵ_l is the lateral strain, which more explicitly is the ratio of the change in width to original width; ϵ_a is the axial strain, the ratio of the change in length to original length.

2.1.1.2.4 Fracture Toughness

Fracture toughness (T) is the strain energy release per unit area of fracture (Dobraszczyk, 1994). In order for a crack to propagate, energy must be supplied to it from the surrounding stressed material where elastic energy is stored as strain energy. Fracture occurs when the rate at which the strain energy is released exceeds the surface energy associated with creating new fracture surfaces. Therefore, fracture only occurs when enough strain energy is put into a body such that bonds break (Dobraszczyk, 1994). The number of bonds that break are proportional to the energy consumed in the cracked body (Dobraszczyk, 1994). There are variations on the general principle of fracture mechanics. The generalized fracture mechanics approach put forward by Andrews (1974) stated that all energy input other than elastic strain energy is included in the determination of fracture toughness. This approach is shown in Equation 5 (Andrews and Bhatti, 1982) .

$$T = k_1(\epsilon_0)cW_{0c} \quad (5)$$

Where: T is the critical apparent energy release rate of "surface work", k_1 is a dimensionless function of strain, ϵ_0 , measured at points remote from the crack, c is crack

length; and, W_{0c} is the input energy density (W_0) when crack propagation occurs (Fahloul and Scanlon, 1996).

There is another approach used for obtaining the fracture toughness of a material; this approach depends on the assumption that the material is brittle. In this approach the critical stress intensity fracture (K_c) is determined from the fracture stress of a material (Vincent, 1982). This approach for brittle materials is given by Equation 6 (Vincent, 1982).

$$T = \frac{K_c^2(1-\nu^2)}{E} \quad (6)$$

Where: T is the fracture toughness, K_c is the critical stress intensity factor where crack initiation takes place, ν is Poisson's ratio, and E is the elastic modulus.

2.1.1.2.5 The Advantages Associated with Fundamental Tests

Fundamental tests are rigorously defined by equations which scientists love. Fundamental tests measure well-defined mechanical properties (Mohsenin, 1970). Some textural properties can be defined in terms of well-defined mechanical parameters (Mohsenin, 1970).

2.1.1.2.5.1 Elastic Modulus

Finney (1969) proposed that the modulus of elasticity could be used to describe the textural characteristic of firmness in fruits and vegetables. Mohsenin (1970) stated that the elastic modulus is a well-defined fundamental mechanical property, which can be used to characterize the texture parameter of tenderness of cooked meat.

An important textural quality of french fries is the limpness of the fry. Limpness is dependent on many factors such as internal moisture content, degree of dehydration of the crust, crispness of the crust and other physical properties of the fry (Voisey *et al.*, 1974). Voisey *et al.* (1974) used the Droopmeter to show that as the specific gravity of the potatoes increased the apparent elastic modulus of the french fry increased. It was also shown by Voisey *et al.* (1974) that a longer cooking time also increased the apparent elastic modulus of the french fry, thus indicating a definite relationship between the physical properties of fries and the processing regime used to fabricate them. Also, Dupont *et al.*, (1992) used an Instron three point bend test to measure the apparent elastic modulus of french fries.

2.1.1.2.5.2 Yield Stress and Fracture Stress

Yield force is an important mechanical parameter that can be used to characterize the textural quality of foods (Mohsenin, 1970). Yield stress is a mechanical property that can be obtained from yield force. Yield stress is defined as yield force per unit area. Many researchers have noted the effectiveness of these single force measurements for obtaining an index of textural quality for fruit, vegetables, butter, or margarine (Bourne, 1975; deMan, 1969; Finney, 1969). Dupont *et al.* (1992) used an objective impact pendulum test at both low and high strain rates to obtain the strength or fracture stress of french fries. Correlation was made between sensory and instrumental measurements based on crispness and mechanical strength (Dupont *et al.*, 1992).

2.1.1.2.5.3 Poisson's Ratio

Poisson's ratio is an important property relating the shape and size changes in deformed materials (Hammerle and McClure, 1971). The Poisson's ratio of isotropic materials range in value from 0 to 0.5. Examples of engineering materials' Poisson's ratio include 0.29 for steel and 0.5 for rubber (Beer and Johnston, 1992). The Poisson's ratio of a potato was reported in the literature to be 0.492 (Voisey *et al.*, 1969).

2.1.1.2.5.4 Fracture Toughness

Many authors from the engineering discipline have characterized the fracture toughness of different industrial materials (Andrews and Bhatti, 1982; Andrews and Fukahori, 1977; Burford and Pittolo, 1986; Hashemi and Williams, 1984). The fracture properties of biological materials have also been examined with the aim of defining texture (Dobraszczyk, 1994; Fahloul and Scanlon, 1996).

Using the generalized fracture mechanics theory postulated by Andrews (1974) it is possible to determine the energy consumption during the fracture of solids in general without being limited to the criterion of their linearity, elastic behaviour, or infinitesimal strain (Andrews, 1974). The generalized fracture mechanics theory as postulated by Andrews (1974) defines fracture propagation from an edge crack of a tensile specimen. It has been shown by Fahloul and Scanlon (1996) that the generalized fracture mechanics theory originally developed and applied to industrial materials is applicable to potatoes. They found Shepody potatoes to have a fracture toughness value of 212 Jm^{-2} .

There is another method of determining the fracture toughness of materials by assuming that the mode of fracture is brittle (Vincent, 1982). Vincent (1982) used this method to determine that the fracture toughness of grass was 30 Jm^{-2} .

Dobraszczyk (1994) utilized the concepts of fracture mechanics to quantify the fracture behaviour of vitreous and mealy wheat endosperm, which can be viewed as a particle composite, during the milling process. Large particles will fracture by crack initiation and brittle fracture; small particles will fracture as a result of plastic deformation and rupture (Dobraszczyk, 1994). The fracture toughness values for vitreous and mealy endosperm were 130 and 50 Jm^{-2} , respectively (Dobraszczyk, 1994).

2.1.1.2.6 The Disadvantages Associated with Fundamental Tests

It must be realized that these well-defined fundamental equations are not ideal for obtaining food texture measurements. These fundamental tests were developed by scientists and engineers interested in the theory and practice of materials of construction (Bourne, 1994). The assumptions that must be made which make these tests applicable to measuring the mechanical properties of building materials often do not apply to foods. Fundamental tests generally assume: small strains of the order of 1-3%; the material is isotropic and homogeneous; and that the test piece is of uniform and regular shape. Most foods fail to comply with these assumptions which may be why fundamental tests often correlate poorly with sensory tests (Mohsenin, 1970).

Also, fundamental tests are generally slower to perform than empirical tests due to more precise sample preparation and analysis of results (Bourne, 1994). For example, the bending test has been used to measure the rheological properties of food materials

(Kapsalis *et al.*, 1972; Somers, 1966). Yet this method is unsuitable for french fries because the apparatus is unsuitable for french fries (Voisey *et al.*, 1974). The holder is too small and there are large errors inherent in the method due to applying the simple bending theory to thin beams bent at small radii of curvature. (Voisey *et al.*, 1974).

2.1.2 Empirical Tests versus Fundamental Tests

Comparison of empirical tests against fundamental tests indicates that there are both advantages and disadvantages associated with each test. Therefore, there seems to be a crossroads that has been reached in regards to texture testing. Bourne (1994) aptly described the dilemma, “As scientists we favour fundamental tests because they are well defined, but as food processors we favour empirical tests because they work and are well correlated with sensory tests.” An approach to this dilemma is to rigorously study empirical tests to understand their principles and reasons for their successes (Bourne 1994). The idea is to seek to obtain fundamental mechanical parameters from empirical tests that are widely used in the food industry. In essence, it would be ideal to convert an empirical test into a fundamental test. Of the tests described above (Sections 2.1.1.2.5.1-2.1.1.2.5.4), indentation would appear to be a suitable candidate for deriving fundamental measurements. Indentation is one of the most simple and widely used type of empirical instrumental test in the food industry (Bourne, 1982). Also, with indentation testing the test specimen is not limited to being a solid self-supporting material; any type of material can be tested (for example pudding and yoghurt in a container (Oakenfull *et al.*, 1989)). Therefore the establishment of indentation testing as a fundamental test rather than an empirical test should be investigated; the purpose being to obtain indices of texture

characterized by fundamental parameters from a test that is widely used in the food industry.

2.2 Indentation Testing-Food Science Research And Engineering Research

The indentation test or puncture test measures the force or load required to push an indenter into a food (Bourne, 1982). The test is characterized by a force measuring instrument, and penetration of the indenter into the food causing irreversible crushing or flowing of the food. The first food indentation test was developed by Lipowitz, who in 1861, placed a flat disk 1 or 2 inches in diameter on the surface of a gelatin jelly in a beaker (Bourne, 1982). The flat disk was connected to a funnel by means of a vertical iron rod, and lead shot was slowly poured into the funnel until there was just sufficient weight to make the disk penetrate the jelly. The total weight of the shot, funnel, rod, and disk was used as a measure of jelly consistency. This early test, although primitive, contains the essential element of an indentation test namely, an indenter that penetrates into the food, application of an increasing force and measurement of the yield point force (Bourne, 1982). This apparatus evolved into the Bloom Gelometer which to this day is used heavily in the jam and jelly industry (Bourne, 1982).

2.2.1 Food Science Research

Some food scientists have studied empirical indentation tests with a fundamental approach. The indentation process has been studied analytically in the engineering field. Bourne (1982) indicated that an interesting fact borrowed from engineers by food scientists was that the theoretical stress distribution under an indenter acting against a semi-infinite

elastic body follows the Boussinesq equation:

$$\sigma = F/2\pi b(b^2 - r^2)^{1/2} \quad (7)$$

Where: σ is the stress at any point under the indenter, F is the total load applied to indenter, b is the radius of indenter, and r is the distance from centre of indenter to stressed area. According to this equation the stress in the food is infinite at the perimeter of the indenter and lowest at the centre of the indenter.

This led to work by Bourne (1966) in which he examined and tried to explain the indentation process for various food materials. It was determined that upon indentation the yield force (the load where penetration occurs) is proportional to both the area and perimeter of the indenter and to the different textural properties of the food being tested. He reasoned that the yield force consisted of two components: compression and shear. The component of the force due to compression of the food under the indenter is proportional to the area of the indenter. The component of the force due to shearing around the indenter is proportional to the perimeter of the indenter. Using these fundamental ideas Bourne (1966) formulated the following equation:

$$F = K_c A + K_s P + C \quad (8)$$

Where: F is the load on the indenter, K_c is the compression coefficient, K_s is the shear coefficient, A is the area of the indenter, P is the perimeter of the indenter, and C is the constant. A plot of F vs. A gives an intercept of $K_s P + C$ and a slope of K_c if perimeter is kept constant. A plot of F vs. P gives an intercept of $K_c A + C$ and a slope of K_s if the area is kept constant. Since the values of K_s and K_c can be obtained from the slopes of these lines it follows that the constant C can also be obtained from taking the intercept and known values for either $K_s P$ or $K_c A$ and calculating the value for C . The physical meaning of the

constant C would be interpreted from equation (8) as being the force required to penetrate the commodity with an indenter of zero area and zero perimeter. The constant C has a value close to zero for most commodities and it can be neglected (Bourne, 1975). Therefore, it is possible to evaluate all the parameters in equation (8) from the force measurements made with a series of different sized indenters (Bourne, 1966). This was an important stage in the conversion of an empirical test into a fundamental test. The arbitrary nature of the indentation test has been removed

For circular indenters, their area and perimeter can be substituted by functions of diameter to give the following equation.

$$F = (\pi/4)K_c D^2 + \pi K_s D + C \quad (9)$$

Where: D is the diameter of the indenter, K_c is the compression coefficient, K_s is the shear coefficient, and C is the constant. It is possible to obtain numerical values for the shear and compression coefficient of a food by using a set of circular shaped indenters (Bourne, 1975). Dividing equation 9 by area and perimeter of the indenter will respectively give:

$$F/A = 4K_s/D + K_c + 4C/A \quad (10)$$

$$F/P = K_c D/4 + K_s + C/P \quad (11)$$

A plot of F/A vs. $1/D$ will give a straight line with a slope of $4K_s$ and an intercept of $K_c + 4C/A$. A plot of F/P vs. D will give a straight line with a slope of $K_c/4$ and an intercept of $K_s + C/P$ (Bourne, 1975).

It should be noted that the compression and shear coefficients, K_c and K_s , respectively, are quoted in fundamental units. This is a great improvement in fundamental understanding. However, these compression and shear coefficients that define the failure of a foodstuff do not exclusively characterize texture.

2.2.2 Engineering Research

As noted, there are defined mechanical properties associated with inherent qualities of a food (Mohsenin, 1970). Fundamental mechanical parameters, such as elastic modulus, Poisson's ratio, yield stress, fracture toughness, are obtained from standardized testing methods (Beer and Johnston, 1992).

The interpretation of an indentation test in terms of stress-strain relations of the material, in comparison to simple compression, is not straightforward on account of the complex strain field produced by the indentation process (Johnson, 1970). With compression testing the contact conditions involving the specimen geometry and edge constraints are well understood. Therefore the values of elastic modulus and yield stress, independent of testing conditions, can be obtained (Johnson, 1970). Yet, it has been acknowledged that indentation testing is a very simple, effective and widely used method of texture evaluation (Voisey *et al.*, 1969). The indentation test provides a very simple non-destructive means for assessing the resistance of a material to plastic deformation (Johnson, 1970).

Indentation testing has been studied analytically in the discipline of engineering with the aim of obtaining a fundamental mechanical parameter, namely, elastic modulus (Briscoe and Sebastian; 1993; Briscoe *et al.*, 1994; Timbers *et al.*, 1965). As an example, this approach has been used on synthetic biological materials, namely, rubber. In the rubber industry there are numerous indentation hardness test methods used for quality control in elastomer production (Briscoe and Sebastian, 1993). The empirical international rubber hardness (IRH) test is a popular indentation test method. The empirical IRH value gives an index of the quality of the rubber. It was found that there is a relationship between the empirical hardness value given by the IRH test and elastic modulus (Briscoe and Sebastian,

1993; Briscoe *et al.*, 1994). Thus, fundamental mechanical parameters of polymers have been obtained with the indentation test. In 1965 Sneddon formulated a fundamental equation relating load-deformation of isotropic materials for the indentation test. This fundamental equation is given as follows:

$$P/d = 2Eb/(1-\nu^2) \quad (12)$$

Where: P is the load, d = deformation, E = compressive elastic modulus, b = indenter radius, and ν = Poisson's ratio.

2.3 Mechanical Testing Of Composites

2.3.1 French Fries as Composite Materials

The recent interest in the advanced composite materials in the aerospace industry has led to an increase in the study and research of anisotropic elasticity (Sakamoto *et al.*, 1991). The design methods developed in the discipline of mechanical engineering can be very helpful in the analysis of biological composite materials (Sakamoto *et al.*, 1991). Large numbers of potatoes are being used for processing purposes and the matter of texture of raw and finished products has become very important. There is no standard method of measuring the textural characteristics of french fries. The textural properties of french fries are not easily determined because of their structure. A french fry consists of two components, a crisp exterior (the crust) and a soft mealy interior (the core) (Voisey *et al.*, 1974). Therefore, french fries can be considered to be a composite material since there are two components that differ in their elastic properties. These two components namely, the crust and the core, characterize the texture of a french fry. The texture of french fries is controlled by many different parameters.

2.3.1.1 Effect Of Cellular Constituents On French Fry Texture

Textural measurements relating the quality of french fries have been related to the cellular arrangement, cell size, starch content, cell wall and interlamellar materials, and middle lamellar materials (Hughes *et al.*, 1975; Voisey *et al.*, 1974).

2.3.1.1.1 Cellular Arrangement

Talburt *et al.* (1987b) stated that the potato is a tuber or a thickened underground stem. The outer skin consists of corky periderm that is 6-14 cells deep. Under the periderm is the cortex, which is a narrow layer of parenchyma tissue, vascular storage parenchyma, which is high in starch and lies within the cells of the cortex. Xylem and phloem are found in minute strands or bundles, most of which form a narrow, discontinuous ring, which is the vascular ring, somewhat within the boundary between the cortex and the vascular area. Forming a small central core but radiating to each of the eyes (the lateral buds) is the pith. The pith consists of primary cells containing less starch than cells in the vascular area and the innermost part of the cortex.

There is a great variation of types of cells and starch contents of such cells within a tuber (Talburt *et al.*, 1987b). The pith can range from 6-12% solids in tubers. As already mentioned, this tissue is low in starch, and french fries containing such tissue may be soggy, limp and totally undesirable in terms of texture (Mohr, 1972). The cortical tissue underlying the periderm or the skin has the highest total solids of any tissue zone in the potato. This part of the potato consists of 20-28 % total solids (Talburt *et al.*, 1987b). French fry strips containing much cortical tissue were described as having a more crisp crust and being more rigid than french fries containing pith (Mohr, 1972; Talburt *et al.*,

1987b). Therefore, the texture of french fry strips will vary within the same tuber and will be dependent upon the location where the french fry strips were obtained (Agblor and Scanlon, 1998; Anzaldúa-Morales *et al.*, 1992).

2.3.1.1.2 Starch Content

Starch constitutes 65-85% of the dry weight of potatoes and affects french fry texture (Talbert *et al.*, 1987b). French fries processed from potatoes with a high starch content have been noted to have the sensory descriptions of a crisp crust, and a mealy interior (DuPont *et al.*, 1992; Talbert *et al.*, 1987b).

The specific gravity of a potato has been found to be directly related to its starch content (Talbert *et al.*, 1987b). Specific gravity is extensively used by potato processors to assess the suitability for the production of french fries (Lulai and Orr, 1979). Normally, the raw potatoes used for processing into french fries usually have specific gravity between 1.080 and 1.120 (Lisinska and Leszczynski, 1989). High specific gravity or high starch content is important for obtaining a high yield of high quality french fries (Lisinska and Leszczynski, 1989). French fries processed from high specific gravity/high starch content potatoes absorb less fat upon frying, which may account for the fact that they produce french fries with a crisp crust (Lulai and Orr, 1979).

2.3.1.1.3 Cell Wall

When a cooked potato is subjected to external forces it fails, and upon examination of the mode of failure there is an indication that separation of the surfaces occurs between the middle lamella and the cell wall (Andersson *et al.*, 1994). The primary cell wall of a

potato cell consists of cellulose microfibrils that are loosely woven together in an irregular pattern and embedded in an amorphous matrix composed mainly of pectic substances and hemicellulose. Its structure has been likened to that of reinforced concrete (Andersson *et al.*, 1994). The secondary cell wall, which lies immediately inside the primary cell wall also consists of cellulose microfibrils embedded in an amorphous matrix of hemicellulose and lignin. It should be noted that the cell wall and interlamellar layer, which usually constitute 1-3% of the weight of the potato, impart a solid structure to a structure that is mostly water (Andersson *et al.*, 1994).

2.3.1.1.4 Middle Lamella

The middle lamella influences the texture of french fries (Jaswal, 1969). The middle lamella is an amorphous layer external to the primary cell wall that cements the individual cells together (Andersson *et al.*, 1994). The interlamellar layer consists principally of calcium salts and polymers of galacturonic acid that have been partially esterified with methyl alcohol and is commonly referred to as pectic material. The degree of polymerization and esterification of the polygalacturonide chains and the amount of cross-linking of adjacent pectin molecules by salt bridge formation have profound effects on the physical properties of the middle lamella and the overall texture of processed potatoes (Andersson *et al.*, 1994; Lineham and Hughes, 1969a).

Partially esterified polygalacturonic acid of very high molecular weight is called protopectin. Protopectin is water insoluble and imparts strength to the tissue. As the potato matures the chain length of the pectin polymer decreases (due to polygalacturonase activity) forming a water soluble pectin which is not as strong as protopectin and the

texture softens (Andersson *et al.*, 1994; Jaswal, 1969). Water soluble pectin can be either high methoxyl content pectinic acid or low methoxyl content pectic acid.

The changes in pectins are caused by two groups of enzymes: 1) pectin methyl esterase (PME), which catalyzes the de-esterification of pectin yielding free polygalacturonic acid and 2) polygalacturonases which catalyze the splitting of the 1-4 glycosidic bonds of the pectin molecule (Andersson *et al.*, 1994; Jaswal, 1969).

Variations in the chemical composition of the cell wall interlamellar matrix affect texture via intercellular adhesion in two ways (Andersson *et al.*, 1994). Firstly, matrix composition may affect the degree of water uptake. Secondly, it affects the viscosity of the hydrated matrix. A high degree of methylation (pectinic acid) of pectic substances increases water uptake on cooking and reduces matrix viscosity causing a decrease in adhesion (Andersson *et al.*, 1994). French fries processed from potatoes with a high pectinic acid content have been described as having a limp and soggy texture (Jaswal, 1969).

2.3.1.1.5 Cell Size

Cell size affects the texture of cooked potatoes (Andersson *et al.*, 1994). There is disagreement in the literature as to whether cell size changes during cooking (Reeve, 1967; Bretzloff, 1970). This is related to the two different schools of thought on the factors affecting the texture of cooked potatoes. Those that view the sensory parameter of mealiness, which is a favourable textural attribute of a french fry, being due to cell rounding, support the theory that cell size changes during cooking (Reeve, 1967). Those

viewing mealiness as a 'viscosity' measure do not believe that there are changes in cell size upon cooking (Warren and Woodman, 1974).

A definite relationship has been found between cell size and the reduction of intercellular cohesion upon cooking which results in a mealy texture (Andersson *et al.*, 1994; Lineham and Hughes, 1969b). It is thought that smaller cells, which have a greater surface area per unit volume of tissue lead to a greater strength for the potato tissue. Starch granule size also affects texture. Potato varieties with large starch granules are described as having a mealy texture upon cooking (Andersson *et al.*, 1994; Warren *et al.*, 1975). Larger starch granules occur most abundantly in the large storage parenchyma cells associated with the internal phloem, and in the water core pith parenchyma but in much less abundance in the storage parenchyma (Reeve, 1967). Large starch granules are however very numerous in smaller cortical parenchyma cells between the vascular bundle ring and the skin. This area contains the most starch per unit volume (Reeve, 1967). In general, varieties having starch granules smaller than average, and have on average smaller storage parenchyma cells, tend to be less mealy in terms of texture (Andersson *et al.*, 1994). Differences in the size of the starch granules are associated with differences in amylose and amylopectin content. Small granules contain less amylose and gel at higher temperatures than larger starch granules (Andersson *et al.*, 1994). This fact follows the findings that higher amylose contents are conducive to a mealy and more viscous texture in cooked potatoes.

2.3.1.2 The Effect Of Processing Conditions On French Fry Texture

The main steps in processing frozen french fries that affect the texture of french fries are 1) blanching, 2) drying; 3) freezing; and 4) frying.

2.3.1.2.1 Blanching

There are three reasons why potatoes being processed into french fries are blanched. Blanching is performed to leach reducing sugars in order to lessen the extent of the browning reaction upon frying. Blanching also destroys enzymes that will cause quality degradation during freezing. Blanching modifies the texture of the potato via the gelatinization of starch and modification of the lamellar substances. When the starch of a potato is raised above 50 C, starch gelatinization occurs (Andersson *et al.*, 1994).

The method of blanching used in industry is to pre-heat the potatoes in water at 85 C for 2 minutes (Lingle, 1988). There are many consequences of blanching at a cellular level and these consequences manifest themselves as textural changes.

2.3.1.2.1.1 Cellular Consequences of Blanching

Blanching causes a permanent modification of the cellular structure in the potato tissue (Andersson *et al.*, 1994; Hughes *et al.*, 1975). The heat treatment step of blanching affects the typical potato cell by altering the cytoplasmic membrane. Heat destroys the differential permeability of the membrane so water enters the cells and the intercellular spaces, expelling gases and other volatiles, and there is also a loss of water soluble nutrients (sugars, vitamins, and minerals) to the blanch water (Andersson *et al.*, 1994). Also, starch gelatinizes and protopectins are modified. Cell walls are altered very little if

altered at all. The destruction of the cell membrane causes a loss of turgor pressure, the factor responsible for the stiffness of raw potatoes (Brown, 1977).

There are also profound changes that occur during blanching at temperatures between 66-73 C due to alterations of the pectic material in the potato (Andersson *et al.*, 1994). Pectin methyl esterase (PME) activity is optimized at temperatures greater than 50 and less than 86 C. PME reacts with the pectins of the middle lamella causing the production of methyl alcohol and reducing the methoxyl content of the pectin. PME is a highly specific enzyme removing methoxyl groups by hydrolyzing methoxyl groups leaving carboxyl groups in place. The result is a decrease of pectin solubility which translates into a firmer texture and therefore greater intercellular cohesion. Above 86 C, PME is destroyed and exerts no influence on the pectic substances thus a cooked potato, and ultimately the french fry, will have a soft and soggy texture if blanched at temperatures greater than 86 C (Andersson *et al.*, 1994).

2.3.1.2.1.2 Blanching Conditions-Time/Temperature Regimes

Different blanching conditions cause different effects on the texture of the potato and ultimately the texture of the french fry (Agblor and Scanlon, 1998; Canet *et al.*, 1984). Different time/temperature combinations have been looked at in order to produce an end product of high quality. Yet, optimal conditions to leach reducing sugars (LTLT (low temperature-long time)) are in contrast to those which cause enzyme inactivation (HTST (high temperature-short time)) and for optimum texture, answers are yet to be found (Canet and Espinosa, 1984).

2.3.1.2.1.3 Blanching Conditions- Chemical Additives

The addition of divalent ions to blanch water affects texture (Andersson *et al.*, 1994). It has been stated that strongly bonded protopectin is important to the texture of french fries (Jaswal, 1969). The addition of 0.5% calcium chloride was found to improve the final texture of french fries processed from low specific gravity potatoes (Jaswal, 1969). Divalent salts improve texture by the fact that the divalent cations strengthen the protopectin molecule (responsible for the rigidity of the cell wall) by causing a crosslinking of the pectinic acid chains (Andersson *et al.*, 1994). The effect of pH on the blanching medium will also affect texture (Andersson *et al.*, 1994). Pectic substances are stable at pH 3 so increasing the pH above 3 means a loss of firmness. The effectiveness of added acid can be attributed to its inhibitory effect on the enzyme polygalacturonase. Furthermore, pH and calcium have been found to be interrelated because when calcium crosslinks the pectin, hydrogen chloride is produced and the pH decreases causing a firmer texture (Andersson *et al.*, 1994; Hughes *et al.*, 1975).

2.3.1.2.2 Drying

It is important to remove excess moisture from the surface of strips after blanching since it has a destructive effect on the fat used for frying (Lisinska and Leszczynski, 1989). The moisture content attained in industry is usually between 62-66% (Lingle, 1988). There is less time required for the frying process for potato strips with a low moisture content. Consequently less oil will be absorbed on frying (Lisinska and Leszczynski, 1989). Higher initial water content allows for increased oil uptake (Gamble *et al.*, 1987; Pinthus *et al.*, 1993).

The temperature of drying has an effect on the cellular structure of the potato. Wang and Brennan (1995) used light microscopy to study the structural changes in a potato at different drying temperatures. The changes in the structure of cells during the drying step are due to shrinkage of cells, increased porosity of the material and a redistribution of moisture. At a low drying rate the amount of shrinkage of the cells bears a simple relationship with the amount of moisture removed. The moisture content at the centre of the strip is never very much greater than that at the surface. Towards the end of drying shrinkage is reduced so that the final size and shape of the material is fixed before drying is complete. At a high drying rate the outer layers of the material becomes rigid and the final volume is fixed early on. As drying proceeds, the tissues split and rupture internally forming an open structure so that porosity is greater at higher drying temperatures (Wang and Brennan, 1995). Case hardening occurs at high drying temperatures. Case hardening is characterized by the rate of moisture removal from the surface of the food being faster than the rate of moisture diffusion from the interior to the food to the surface. This phenomenon manifests itself as a hard layer formed on the food thereby hindering any further moisture loss. Therefore, case hardening will affect the texture of the french fry in terms of both crust and core. French fries exhibiting a case hardened crust will have a tougher crust. The core of a french fry that is characterized by case hardening will be more moist and compliant since there is more moisture present in the core (Reeve and Neel, 1960).

2.3.1.2.3 Freezing

Freezing is a convenient means of food preservation. Nevertheless, freezing is responsible for profound texture changes in fruits and vegetables (Brown, 1977). A major cause of texture change is due to irreversible separation of water from the protoplasm, even when cell walls remain intact. Just as drying and the rate of drying affect cellular structure, the rate of freezing affects cellular structure. Canet and Espinosa (1984) studied the effect of the rate of freezing on the texture of blanched potatoes using shear rupture force as an index of texture. It was found that there was no difference between the cooked control and the sample frozen with a “quick freeze” method. There was a significant difference between the shear rupture force of the cooked control and the sample frozen slowly. The difference between slow freezing and quick freezing is attributable to the method of ice crystal formation and it manifests itself in terms of textural differences. Slow freezing causes the formation of large extracellular ice crystals where more cellular damage is incurred. Quick freezing produces small intracellular and extracellular ice crystals. This allows for the preservation of original cellular structure thereby affecting the texture of the french fry (Canet and Espinosa, 1984). Freezing would be expected to influence the texture of the interior/core of a french fry more than the crust of a french fry seeing that the crust is dehydrated while the core still contain significant amounts of water.

2.3.1.2.4 Frying

During the processing of french fries there is the blanching step, which is a cooking of the potatoes with moist heat. There is a disintegration of cell membranes, softening of cellulosic materials, and large amounts of protopectin change to pectin. Softening is due to

loss of the cohesive/adhesive qualities of the middle lamella (Andersson *et al.*, 1994). Deep fat frying can be assumed to have somewhat different effects since it is essentially a surface cooking and dehydration process during which the starch content of the cell is gelled and dehydrated (Singh, 1995). The process of frying involves the loss of water and the absorption of oil; strongly associated with this loss of water and oil absorption is the formation of a crust (Pinthus *et al.*, 1993; Reeve and Neel, 1960). The crust is formed as oil is absorbed into the fry. Many factors affect oil uptake. These factors include oil quality, product and oil temperature, frying duration, product shape and product content, porosity, pre-frying treatments, coating and surface roughness (Pinthus *et al.*, 1993). Some relationships which have been found include: there is negative linear relationship between oil content and specific gravity (Lulai and Orr, 1979); the depth of the crust equals the depth of oil penetration (Pinthus *et al.*, 1995); and crust thickness is dependent on the length of frying time and temperature of the oil (Pinthus *et al.*, 1995).

Oil penetrates mainly the cellulosic walls and to some extent the gelled starch contents of crust cells. Oil penetration is influenced by oil type and oil quality. Some oil is absorbed onto cell wall surfaces of the interior voids developed during frying. Cells tend to separate when steam is evolved from the strips during frying. Oil uptake during deep fat frying of products, such as potatoes, which initially contain little or no fat takes place at the surface of the product (Pinthus and Saguy, 1994; Pinthus, *et al.*, 1995).

Oil uptake has been noted to affect the amount of water the product lost during frying (Pinthus and Saguy, 1994). The crust, which is formed on the surface of food during the process, may act as a diffusion barrier that limits mass transfer. Crust development influences heat and mass transfer processes, and further oil uptake. Inner moisture converted to steam

may find selective channels in the structure and escape through open capillaries, pores and/or crevasses. Oil that enters the voids left by the water may be important in keeping the structure from collapsing and may contribute to keeping capillaries open (Pinthus and Saguy, 1994).

2.3.2 Footing with an Underlying Soil Mass as a Two-Layer System

In the literature, a footing with an underlying soil mass has been viewed as a two-layer system (Burmeister, 1945b). The soil and the footing differ in their elastic properties and therefore the system as a whole differs (Selvadurai, 1979). Thus, the stresses and deformations encountered in a two-layer system must be considered in solving the soil-footing problem. The footing is the top structural unit, which rests on the soil mass, and is considered to be stiffer and sometimes infinitely stiff in comparison to the soil. Burmeister (1945a) examined the soil-footing problem with respect to repeated heavy loadings due to airplane landings. Sneddon (1965) stated the importance of analyzing the soil-footing problem in order to determine the safety of pillars resting on a soil-footing system. Although, the mechanical response of a soil is very complex and usually cannot be considered elastic, the model of an elastic medium is usually accepted and is sufficiently accurate to describe the soil-footing interaction (Ascione and Grimaldi, 1984).

The interaction problem between an overlying footing (considered as an elastic layer) and the underlying soil mass (considered as the Winkler foundation) has been studied using idealized models such as the Winkler model (see 2.3.2.1) and analytical solutions can be obtained for these problems (Selvadurai, 1979). To be able to accurately characterize the behaviour of a soil mass as being equivalent to that of a Winkler foundation, the application

of assumptions to the problem is necessary (see 2.3.2.1). If the assumptions are satisfied, the mathematical equivalence between the soil mass and the Winkler foundation is established (Selvadurai, 1979).

2.3.2.1 The Winkler Model

The Winkler model is an example of an elastic model which shows the physical view of how an elastic material or an elastic medium will deform under the application of an external force (Selvadurai, 1979). The Winkler model can be viewed as a system of mutually independent spring elements. An important assumption of the Winkler model is that deformation occurs only under the applied load; outside this region there is no deformation regardless of the location or of the magnitude of the applied load (Selvadurai, 1979). The Winkler model also assumes that the deformation of the medium at any point of the surface is directly proportional to the stress at that point (Selvadurai, 1979). The foundation stiffness (k) is the constant of proportionality between applied normal stress at a point and the corresponding surface deflection. For a homogenous Winkler foundation, the value of k is constant at each location. Also, for a homogenous Winkler foundation, the value of k should be independent of the magnitude, or the area of application, of the load (Selvadurai, 1979). However, in practical situations the fundamental assumptions of idealized behaviour may not be completely satisfied. The foundation stiffness may not be constant; it may depend upon the magnitude of the applied stress and the depth of the underlying area (Dempsey *et al.*, 1991). Deviation from the assumption of ideal behaviour imposes some restrictions on the effectiveness of this theoretical analysis (Selvadurai, 1979).

Nevertheless, there are many engineering problems where the Winkler model represents a very accurate characterization of real-life conditions (Selvadurai, 1979). The Winkler model has been used effectively in problems associated with the analysis of soil-footing interactions and floating structures such as floating bridges and ice sheets (Selvadurai, 1979).

2.3.3 Aircraft Wings as Composite Materials

Sandwich panels are described as composite materials. They consist of two laminates (facesheets) with a sheet of different material (the core, normally honeycomb material) embedded in between (Frostig and Baruch, 1990). Usually the facesheets are thin compared with the core. Sandwich panels are assembled and have their different materials intimately fixed in relation to each other so as to use the properties of each to specific structural advantages for the whole assembly (Frostig and Baruch, 1990).

Aircraft wings can be considered to be sandwich structures (Tsang and Dugundji, 1992). The presence of the core complicates the mechanisms of failure of sandwich panels since the core has its own mechanical properties, affects the mechanical properties of the facesheets, and ultimately the sandwich structure. Impacts on sandwich panels with laminated face-sheets can result in substantial strength reduction and face-sheet delaminations (Olsson and McManus, 1996). Typical damage in sandwich panels corresponds with the following description. Core damage occurs prior to facesheet damage and it is core damage that is responsible for the generally compliant contact response of the sandwich panels. As the extent and the depth of local core crushing

progresses, delamination occurs and visible surface fibre damage becomes apparent (Tsang and Dugundji, 1992).

Tsang and Dugundji (1992) studied the damage resistance of aircraft wings under low speed impacts. Experimental load-deformation curves were compared against a theoretical model based on small-deflection theory and the assumption of elastic core behaviour. It was observed that the thickest core panel failed at the highest load and the thinnest core failed at the smallest load. The thicker core panels show better agreement between the theory and experiment than the thinner core ones when no significant damage was present (Tsang and Dugundji, 1992). Williamson and Lagace (1993) stated that core thickness has an important effect on the loading responses of the sandwich panels. The experimental work of Williamson and Lagace (1993) indicated that the maximum contact force generally increased with increasing core thickness, which corresponds with the results of Tsang and Dugundji (1992).

To characterize the failure of aircraft wings, Olsson and McManus (1996) used a theory based on the assumption of axisymmetry, in that the impact damage could be likened to what occurs during axisymmetric loading. Also, their theory was based on the assumption that the load being applied was concentrated on an elastic infinite facesheet which rested on a core that was bonded to a rigid foundation. After core yielding, the contact problem was considered to have separate regions. There was an outer region and an inner region. The outer region was modeled as a plate on an elastic foundation. The inner region was modeled using small deformation theory, large deformation theory, and membrane theory.

Small deformation theory refers to the condition where the deformation incurred is less than half the thickness of the facesheet. The situation is characterized by linear elastic behaviour (Olsson and McManus, 1996). Large deformation theory is used to describe deformation less than the facesheet thickness but greater than half the facesheet thickness. Deformation of this magnitude results in a non-linear load-deformation relationship (Olsson and McManus, 1996). The membrane solution is characterized by the condition where the deformation is greater than the facesheet thickness. For these large deformations, the middle surface of the facesheet becomes appreciably strained and carries part of the load as a diaphragm in direct tension. This results in the significant contribution of membrane stress for the corresponding deformation (Roark, 1954).

Olsson and McManus (1996) found that the load history for the indentation of a composite material consists of three regimes: linear elastic, non-linear plastic, and non-linear plastic with membrane stress. Thereby, considering all three of these regimes in the indentation analysis of a composite material, a more accurate theoretical model describing the indentation process was possible.

3.0 PAPER 1

ANALYSIS OF THE ELASTIC MODULUS OF AN AGAR GEL BY INDENTATION

3.1 ABSTRACT

Indentation tests are frequently used in the food industry as a simple means of texture evaluation. However, such indentation tests generally provide empirical results for product texture. This study used the approach taken by Bourne to obtain the compressive and shear components for an agar gel. But in addition, the low strain regime for the same experiments was used to evaluate the gel's elastic modulus using the theory of elasticity. Five flat ended punches of different diameters were used as indentation probes on large slabs of 3% agar gel. Compression testing, using lubricated teflon platens and a travelling microscope, was used to independently measure the gel's elastic modulus (52 kNm^{-2}) and Poisson's ratio (0.32). The compressive and shear coefficients compared favourably with analyses performed by other researchers, and indicated that shear dominated in the failure of the gel under the probe. Indentation measurements of reaction force (P) and deformation (d) were analysed with the theoretical relationship for frictionless flat cylinder indentation. A good linear fit ($r^2 = 0.991$) was obtained for P/d versus indenter radius, indicating the validity of the analysis. However, the value of the elastic modulus derived from indentation was 79 kNm^{-2} , an overestimate of 52%. The larger value suggests that additional factors to those considered in the theoretical model influence the indentation process, such as the presence of pores in the gel, frictional forces during indentation, and elastic mismatch between indenter and gel. Similarity in results for the elastic modulus determined from indentation compared to compression, indicates that a simple testing method can yield a more comprehensive evaluation of food textural quality.

3.2 INTRODUCTION

Texture is an important parameter of food quality and its evaluation is of paramount importance for quality control in a food processing plant (Finney, 1969). The food industry often employs indentation (or penetrometer tests) as an expedient method of texture evaluation (deMan, 1969), but they generally provide empirical results for product texture, rather than fundamental mechanical parameters. This makes comparison of results between different indentation tests very difficult, and many researchers have acknowledged this sentiment (Kamel and deMan, 1975a).

Seeking to address this difficulty, Bourne (1966) derived an equation relating the force required for penetration into a food to the dimensions of the probe used for penetration:

$$F = K_c A + K_s P + C \quad (1)$$

Where: F = the maximum (penetration) force, K_c is the probe area (A) dependent compression coefficient, K_s is the probe perimeter (P) dependent shear coefficient, and C is a constant. This equation characterized the texture of foods by two mechanical parameters (K_c and K_s) expressed in fundamental units. Their validity was independently confirmed by deMan (1969). Bourne (1975) later used flat ended cylindrical probes of different diameters to obtain numerical values for the compression and shear coefficients for many different food products.

However, these shear and compression coefficients that define the failure of a foodstuff do not exclusively characterize texture. There are other defined mechanical properties associated with inherent qualities of a food (Mohsenin, 1970). For example, the

elastic modulus is a fundamental mechanical property which can be used to characterize the texture parameter of tenderness (Mohsenin, 1970), while the shear modulus is important for analyses of gel texture development (Oakenfull *et al.*, 1989). The same indentation (penetrometer) load-deformation tests that are used to derive the compression and shear coefficients can also provide at low strains a fundamental property of an isotropic food, its elastic modulus (Sneddon, 1965) from:

$$P/d = 2Eb/(1-\nu^2) \quad (2)$$

Where: P = load, d = deformation, E = elastic modulus, b = indenter radius, and ν = Poisson's ratio. An example of its use on a synthetic biological material, rubber, has been given by Briscoe and Sebastian (1993) and Briscoe *et al.* (1994).

It was postulated by the author that a mechanics analysis of indentation could be performed alongside measurement of the compression and shear coefficients of a food to measure the food's elastic modulus. Thus, the objective of this research was to show that a comprehensive evaluation of food texture is feasible in a set of simple tests.

3.3 MATERIALS AND METHODS

3.3.1 Agar Gel Preparation

A 3% (w/v) agar gel was prepared by dissolving microbiological grade granulated agar (Difco, Detroit, MI) in distilled water. The solution was heated until boiling in an Erlenmeyer flask on a hot plate. The liquid agar dispersion was poured into a pan and cooled overnight at room temperature for testing 24 hours later (± 2 hours). Bringing the

agar solution to a boil resulted in the formation of bubbles which remained entrapped in the agar gel upon setting.

3.3.2 Compression Testing

All compression testing was performed at room temperature (25 ± 2 C). Cubes of agar gel with 40 mm sides were used for determining Poisson's ratio. A grid was drawn on a square face of an agar cube and its lateral and axial lengths were measured with a travelling microscope in two locations about the centre of the agar cube. The agar cube was compressed under lubricated teflon-coated platens with a normal force at a rate of 22 mm min^{-1} , using an Ottawa Texture Measuring System (OTMS) equipped with a 25lb (110N) load cell (Canners Machinery, Simcoe, ON). Crosshead movement was stopped when a strain of either 1%, 2%, or 4% was attained. The grid's deformed lateral and axial dimensions were measured with a travelling microscope within 45s. Application of the various strains was performed in random order. The agar gel was prepared in triplicate on three separate days and ten cubes were obtained from each pan for a total of 30 values for Poisson's ratio.

A cork borer (15 mm diameter) was used to obtain cylindrical specimens of 15 mm height which were used for measuring the elastic modulus. The cylindrical specimens were compressed to failure with a normal force under lubricated teflon coated platens on a Lloyd L1000 universal testing machine equipped with a 20N load cell (Lloyd Instruments Ltd., Fareham, England). The elastic modulus was calculated from the slope of the force-deformation curve in the 1-4% strain region and from specimen dimensions. The Lloyd

testing machine was used for obtaining the control elastic modulus because it is capable of testing under quasi-static conditions at a crosshead speed of 1 mm min^{-1} , unlike the OTMS machine. A pan of agar gel was prepared on three separate days. Ten values of the elastic modulus were obtained for each pan in order to account for the variability between batches of agar prepared. A total of 30 values of elastic modulus were obtained. These compression to failure experiments were repeated on the OTMS machine at a crosshead speed of 22 mm min^{-1} .

3.3.3 Indentation Testing

The indentation testing was performed at room temperature under quasi-static conditions. The Lloyd testing machine was used for the application of a normal force with a crosshead speed of 1 mm min^{-1} until the gel yielded under the probe. The probes employed for indentation testing were flat ended cylinders with 0.5, 1.0, 2.0, 3.0 and 4.0 mm diameters. Agar cubes of 40 mm sides were indented with one of these probes. These dimensions were used so that the agar specimens could be treated as an elastic half-space (i.e., the area under the indenter is small relative to the size of the specimen) (Mohsenin, 1970). Five pans of agar were prepared for testing. Each pan yielded ten cubes of agar of the desired dimensions. Testing took place over five days with two probes being used for indentation testing on each pan. The probes were paired for indentation testing randomly to minimize experimental error that might be introduced by testing one batch of agar with one probe only. Therefore, ten indentations were performed with each probe. The slope values obtained for the indentation load-deformation tests' curves were determined from

the linear portion of these curves (i.e., in the 0.75-4% strain range). The 0-0.75% strain range was discounted from analysis since complete contact between the indenter and the agar gel did not appear to have been established in this range.

3.4 RESULTS AND DISCUSSION

3.4.1 Poisson's Ratio

Values of Poisson's ratio at 1%, 2%, and 4% strain are presented in Table 1. Since differences between Poisson's ratio at these strains were not significantly different, an overall Poisson's ratio is also quoted in Table 1. The average value of the Poisson's ratio for all of the strains applied was 0.32. This value may seem questionable for a material normally regarded as being incompressible and having a Poisson's ratio of 0.50 commonly cited (Oakenfull *et al.*, 1989; Yano *et al.*, 1987). However, the 3% agar gel prepared was observed to contain air bubbles so it should be considered as a porous medium. For a material that contains a phase that is compressible, even when the principal/continuous phase is incompressible, the material as a complete system can be considered a compressible material (Mackenzie, 1950; Yano *et al.*, 1987). Also, Yano *et al.* (1987) obtained data for a 2% agar-gelatin gel that had a Poisson's ratio that decreased from 0.50 to 0.30 as the porosity of the gel increased. The method of creating the gel in this study would also likely create heterogeneity in the bubble size distribution, which would cause a more rapid decline in Poisson's ratio for a given level of porosity (Mackenzie, 1950; Rice, 1996). Therefore, the value of 0.32 obtained for the Poisson's ratio for the 3% agar gel is reasonable.

TABLE 1.
POISSON'S RATIO AT VARIOUS COMPRESSIVE STRAINS

Strain (%)	Mean Poisson's Ratio	Standard Deviation	Coefficient of Variation (%)
1	0.33 ¹	0.061	18
2	0.31 ¹	0.074	24
4	0.32 ¹	0.079	24
Overall	0.32 ²	0.070	22

¹n = 10
²n = 30

3.4.2 Compressive Elastic Modulus

The value for the elastic modulus obtained under quasi-static loading was 52 ± 3.7 kNm⁻² (95% confidence limits). Work done by Nussinovitch *et al.* (1990) showed that the compressive elastic modulus and the compressive yield stress of a gellan gel were comparable to those of an agar gel of similar concentrations. Therefore, the elastic modulus of a 3% agar gel derived from their experimental work would be approximately 700 kNm⁻². This value is significantly higher than the value obtained using a crosshead speed of 1 mm min⁻¹. The discrepancy may be explained by the effects of strain rate in a viscoelastic material. Nussinovitch *et al.* (1990) used a crosshead speed of 10 mm min⁻¹.

Auxiliary experiments performed on the OTMS, using a crosshead speed of 22 mm min^{-1} , yielded values for the elastic modulus of 499 kNm^{-2} (Table 2).

Similar strain rate effects were observed (Table 2) for the compressive yield stress, determined quasi-statically to be 8.3 kNm^{-2} . This is significantly lower than the value derived from Nussinovitch *et al.* (1990) at approximately 110 kNm^{-2} . The value obtained by the auxiliary experimental work on the OTMS was 90 kNm^{-2} . These latter values do not differ substantially. The greater forces at higher deformation rates can be ascribed to slower crosshead speeds allowing for relaxation and flow of the gel (Munoz *et al.*, 1986). However, literature exists in which the recorded force at failure was independent of the deformation rate. For example, for penetration testing, Kamel and deMan (1977) showed that the maximum force obtained from the penetration of gelatin gels did not vary as crosshead speed was altered from 24 to 72 mm min^{-1} . These speeds are not an order of magnitude greater than each other as are the quasi-static conditions of 1 mm min^{-1} and 22 mm min^{-1} that were utilized in these experiments. Therefore, viscoelastic effects probably do account for the differences in mechanical properties between quasi-static conditions (Table 2) and those cited by Nussinovitch *et al.* (1990). Lelievre *et al.* (1992), showed that increasing strain rate led to greater failure stress for gellan gels, but that failure strains were virtually unchanged. The results for failure strain at 22 mm min^{-1} and 1 mm min^{-1} are significantly different (Table 2), but they do not vary by an order of magnitude as the yield stress values did.

TABLE 2.

EFFECT OF CROSSHEAD SPEED ON THE MEAN (\pm STANDARD DEVIATION) ELASTIC MODULUS, YIELD STRESS AND FAILURE STRAIN DETERMINED BY COMPRESSION ($n = 30$)

Crosshead Speed (mm min ⁻¹)	Elastic Modulus (kNm ⁻²)	Yield Stress (kNm ⁻²)	Failure Strain (%)
1	52 \pm 9.9	8.3 \pm 1.2	15.9 \pm 2.7
22	499 \pm 83	90 \pm 6.8	23.7 \pm 3.7

3.4.3 Indentation Testing

3.4.3.1 Yield Stress Results

Analysis of the yield stress values was modeled after the work of Su and Humphries (1972), as described by Bourne (1975) and Kamel and deMan (1975b). The results for the indentation yield stress values are presented in Table 3. The compressive component and the shear component of the yield stress values were obtained from plots of force/indenter area versus the reciprocal of indenter diameter, and force/indenter perimeter versus indenter diameter (Bourne, 1975). From Figure 1 it can be seen that a good linear relationship was obtained from the F/A plot ($r^2 = 0.994$) to yield a shear coefficient (K_s) of 24.8 Nm⁻¹, and a compression coefficient ($K_c + C/A$) of 3.9 kNm⁻². The linear relationship of the F/P plot (Figure 2) was not as good ($r^2 = 0.717$), but gave values for K_s and K_c of 21.3 Nm⁻¹ and 12.4 kNm⁻², respectively, which is in good agreement with the F/A plot

after neglecting C , since the value of the constant C was found to be close to zero for all concentrations of gelatin gels tested (Kamel and deMan, 1975b). Also, these results are in accordance with the K_s and K_c values obtained by Kamel and deMan (1975b) using flat ended cylindrical punches for the gelatin gels (38 Nm^{-1} and 9 kNm^{-2} , respectively), and by Bourne (1975) using flat ended cylindrical punches for a 2% agar gel (35 Nm^{-1} and 54 kNm^{-2} , respectively).

FIGURE 1. RELATIONSHIP BETWEEN THE FORCE/AREA VERSUS 1/DIAMETER
OF THE INDENTER FOR A 3% AGAR GEL

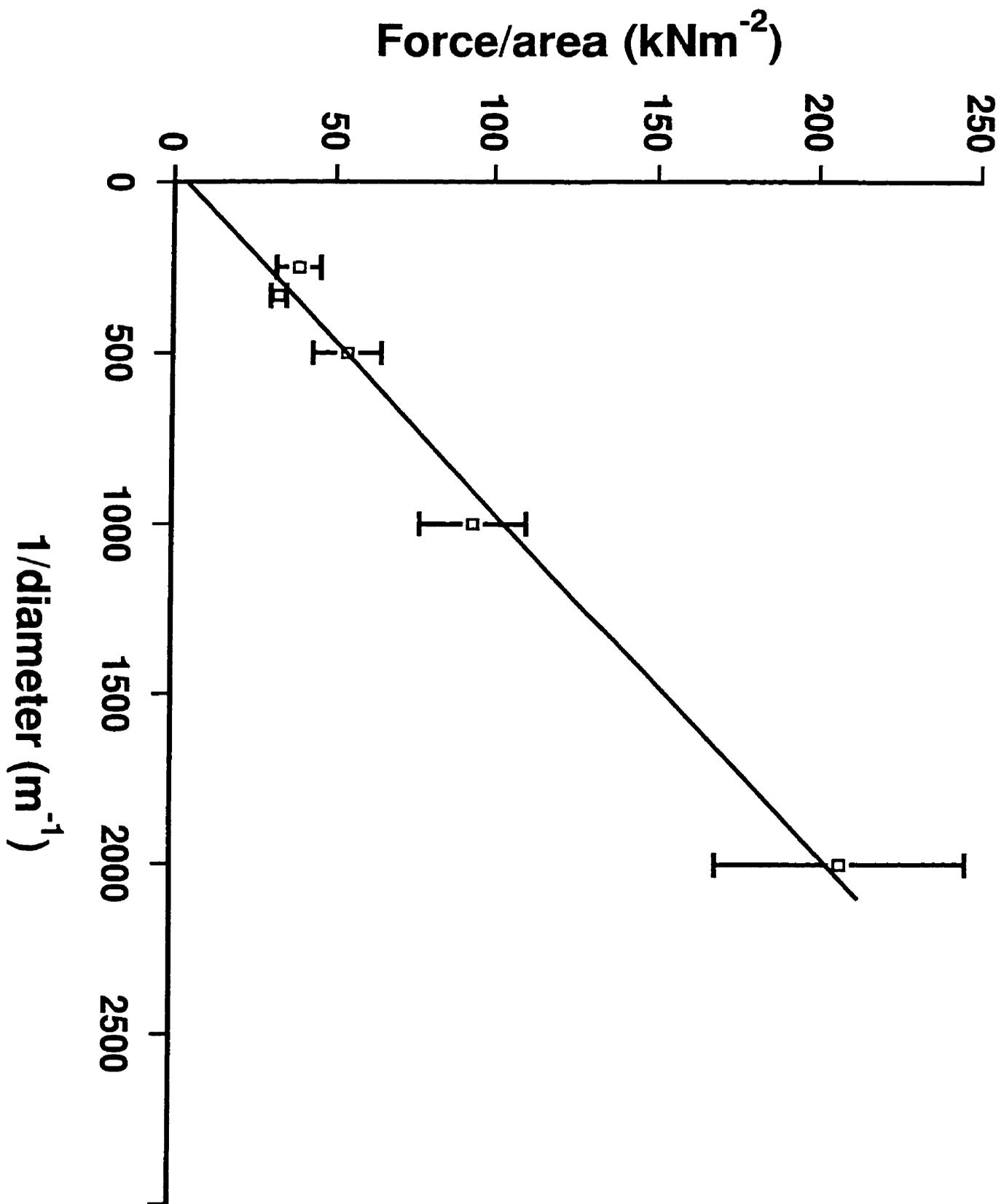
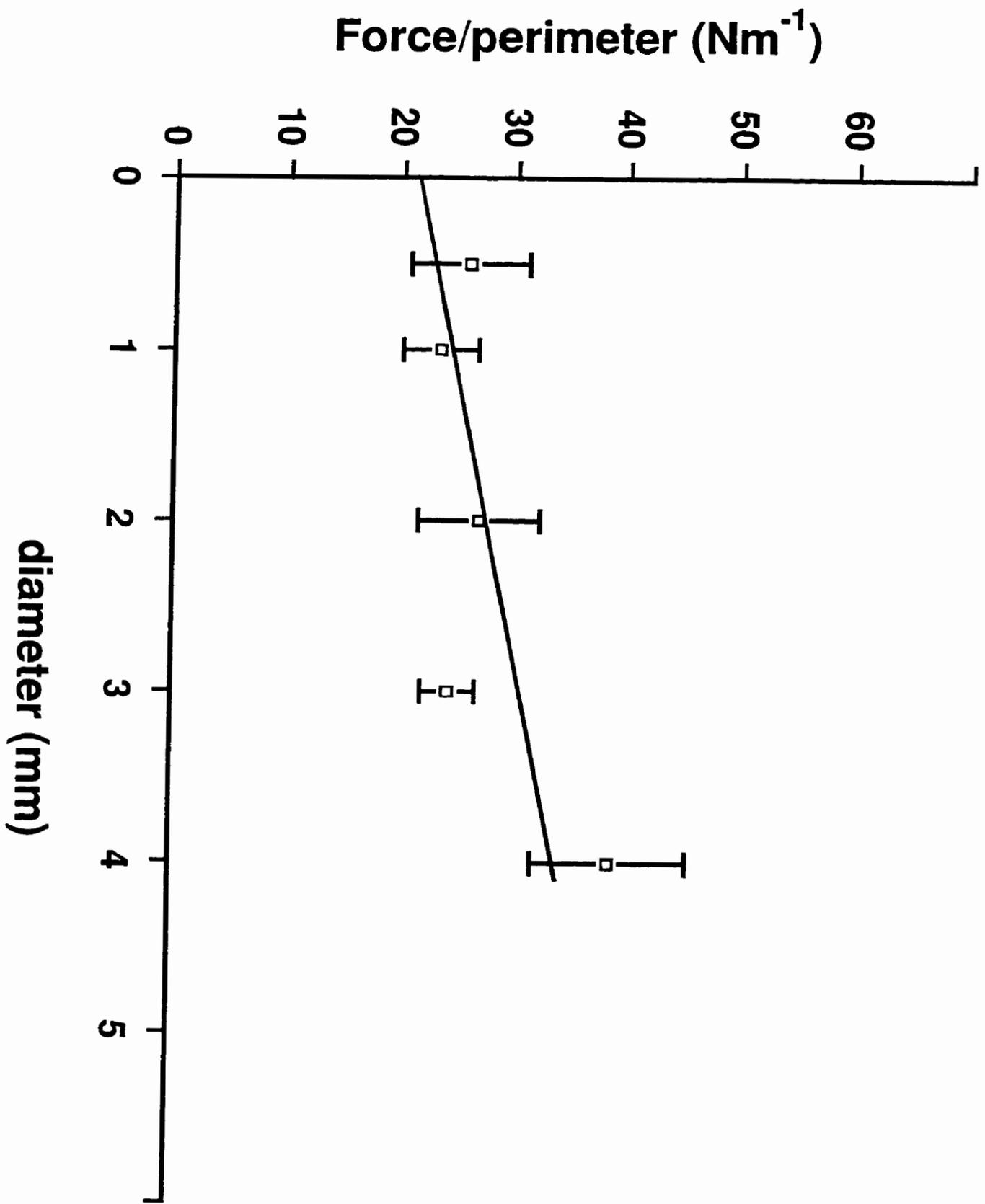


FIGURE 2. RELATIONSHIP BETWEEN THE FORCE/PERIMETER
VERSUS DIAMETER OF THE INDENTER FOR A 3%
AGAR GEL



In all the indentation load-deformation curves, yielding only occurred after a shift from linear to non-linear behaviour. Two factors are likely responsible for the enhanced stiffness after indentation has surpassed the initial stages. Any pores subjected to the compressive stress under the indenter will be preferentially compressed and closed up. Thereafter, there will be greater resistance to the indentation process. Also, water contained in the gel matrix will be expressed. The viscosity of the gel matrix will increase and therefore resistance to the indentation process or resistance of flow of the agar matrix will occur. A similar reasoning was used by Oomens *et al.* (1987) to describe fluid flow occurring when skin was compressed.

Following the approach taken by Peleg and Gomez Brito (1975), the mean values of K_c and K_s were substituted back in Equation 1 to estimate the contribution of shear and compression to the indentation force. The results shown in Table 3 indicate that agar gel's failure under cylindrical punches is dominated by the shear component. This is particularly true for the smaller sized indenters where less volume of material under the surface of the indenter is able to counteract the effect of high stresses at the perimeter of the indenter (Oakenfull *et al.*, 1989; Sneddon, 1965; Timbers *et al.*, 1965).

TABLE 3.
DETERMINATION OF THE DOMINATING FACTOR
(SHEAR OR COMPRESSION) DURING INDENTATION FOR
INDENTERS OF VARIOUS DIAMETER (n = 10)

Indenter Diameter (mm)	Yield Stress (kNm ⁻²)	Experimental Force (N)	Calculated Force (N)	% Contribution to Calculated Force	
				Compression	Shear
0.5	207±54 ^a	0.041	0.038	4	96
1.0	94 ^b ±25	0.073	0.079	8	92
2.0	54±15	0.168	0.170	15	85
3.0	32.4±4.2	0.229	0.275	21	79
4.0	38.6±9.6	0.485	0.392	26	74

^aMean ± standard deviation

^bn = 16

3.4.3.2 Elastic Regime

A theoretical relationship for frictionless indentation with a flat ended cylinder, principally derived by Sneddon (1965), is:

$$P/d = 2bE/(1-\nu^2) \quad (2)$$

Where: P is the reaction force (load), d is the deformation, b is the indenter radius, E is the elastic modulus, and ν is Poisson's ratio. Experimental values of the ratio of reaction force (P) to deformation (d) were obtained from the initial slope of the load-deformation curve

during each of the indentation tests. One can substitute the experimental P/d values into the above equation and, knowing Poisson's ratio (Table 1), obtain the theoretical elastic modulus. These results are shown graphically in Figure 3 with error bars based on 95% confidence intervals. The experimental results are significantly higher than the theoretical model would predict; the slope of the experimental line is approximately $3E/(1-\nu^2)$ rather than the theoretical prediction of $2E/(1-\nu^2)$. However, the experimental results of P/d versus b yield a good linear fit with $r^2 = 0.991$, and the intercept is almost zero (-4kNm^{-2}), indicative of the validity of the treatment. The value of the elastic modulus derived from the indentation experiments was 79 kNm^{-2} . This is an overestimate of 52% compared to the elastic modulus calculated from the compression experiment (Table 2). Briscoe and Sebastian (1993) and Briscoe *et al.* (1994) obtained experimental indentation results that were in close accordance with the theoretical results by using similar analytical equations for various indenters with no defects. Examination with a stereo-microscope indicated no major defects were present on the indenters which could account for the significant difference between experimental and theoretical results.

FIGURE 3. RELATIONSHIP BETWEEN THE RATIO OF LOAD TO DEFORMATION (P/d) AND INDENTER RADIUS (b)
Solid line represents best fit to experimental data; dashed line the theoretical P/d values using $\nu = 0.32$ and $E = 52 \text{ kNm}^{-2}$ (Tables 1 and 2); error bars represent 95% confidence limits.

$P/d \text{ (Nm}^{-1}\text{)}$

0 100 200 300 400

0.0

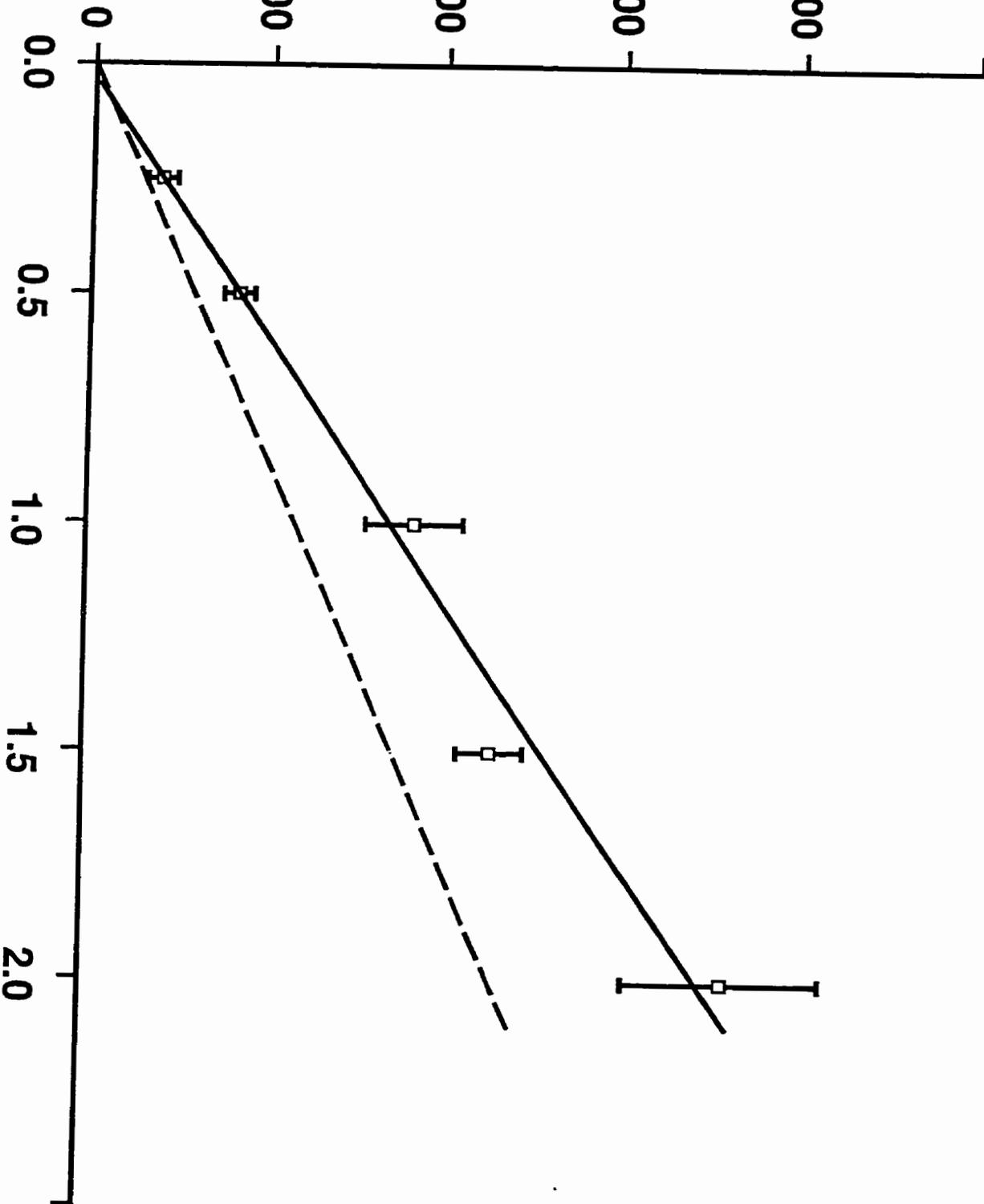
0.5

1.0

1.5

2.0

$b \text{ (mm)}$



Plausible explanations for the difference between the experimental and theoretical results could be due to the elastic mismatch between the steel indenter and the agar gel being indented, and therefore ascribable to the frictional forces that arose during the indentation process (Spence, 1975). Warren and Hills (1994) stated that if the two bodies being indented are dissimilar, the more compliant body (agar gel in this study) will “displace” more. Thus, radial shearing tractions will be incurred and a modified stress field will result. The modified stress field thereby causes a complication of the contact conditions; the contact problem is no longer defined by the criterion suitable for frictionless contact of elastically similar bodies. The elastic mismatch may be quantified by Dundurs’ constant (B) which was given by Warren and Hills (1994) as:

$$B = [(1-2\nu_1)/G_1] - [(1-2\nu_2)/G_2] / 2A \quad (3)$$

Where:

$$A = (1-\nu_1)/G_1 + (1-\nu_2)/G_2 \quad (4)$$

The symbols ν and G refer to the Poisson’s ratio and modulus of rigidity (shear modulus), respectively. The subscripts 1 and 2 refer to the two contacting bodies. The Dundurs’ constant calculated for this experiment was -0.265. This indicates that “stick” will exist over the entire contact area causing deviations from the classical contact conditions of elastically similar bodies. The analysis, by assuming frictionless contact (Timbers *et al.*, 1965), is not fully valid and therefore, to obtain accurate results, the presence of radial shear tractions must be accounted for in future theoretical models.

This factor alone is insufficient to account for the 52% overestimate of the elastic modulus (Spence, 1975). A further possible explanation arises from pores in the gel, and

their effect on how the elastic modulus is determined from compression or indentation. The compressive technique measures the properties of the gel as a whole, including the pores. As a consequence, the mechanical properties of this 'porous composite' are different from those of the gel *per se*, as expected from theoretical considerations (Mackenzie, 1950), and from practical experience on a variety of materials (Rice, 1996; Yano *et al.*, 1987). Generally, the elastic modulus of the porous material is lowered as porosity increases (Rice, 1996; Yano *et al.*, 1987). During indentation, stresses are less uniformly distributed in the gel (Sneddon, 1965). If the reactive force encountered by the indenter arises from stresses set up in a volume of gel that has a lower pore concentration than the gel as a whole, then the elastic modulus derived from indentation testing will be greater.

3.5 CONCLUSIONS

A fundamental mechanics approach used in indentation testing of industrial materials can be used concurrently with more conventional texture testing. There are some problems involved with this approach in that an elastic mismatch exists between the indenter and the biological material being tested because their material properties differ significantly, and inhomogeneity may contribute to loading by an indenter measuring different properties from those of conventional compression tests. These phenomena (and possibly others) caused the theoretical indentation model to overestimate the elastic modulus for 3% agar gel by 52%. Nevertheless, a linear relationship was observed in the experimental data, indicating the validity of the research. Once a quantitative assessment of the contact conditions is achieved and is applied to the theoretical model, indentation

testing can be used to generate fundamental mechanical constants for food texture quality.

4.0 PAPER 2

A FRACTURE MECHANICS ANALYSIS OF THE TEXTURE OF FRIED POTATO CRUST

4.1 ABSTRACT

A fundamental engineering approach was used to quantify the mechanical properties of the fried potato crust. Potato slabs were fried for varying lengths of time in order to see the effect of fry time on the mechanical properties of the crust. Quantitative values for the fracture stress, fracture strain, elastic modulus, and fracture toughness were obtained using the tensile test. Frying time had an effect on the mechanical properties of the fried potato crust. The fracture stress and elastic modulus values increased as fry time increased. Fracture strain and fracture toughness values decreased as fry time increased. The fracture stress and elastic modulus values were in the range of 100 kNm^{-2} and 1 MNm^{-2} , respectively. Fracture strain was in the range of 1-10 % strain. Fracture toughness was of the magnitude of 10 Jm^{-2} . With respect to fracture toughness, as length of fry time increased the crust material changed from a ductile or pliant material to a more brittle material. A quantitative value of the Poisson's ratio was unable to be obtained, but microscopy was employed to deduce that the value was 0.5. The values of mechanical properties obtained for fried potato crust employing the mechanical principles of the tensile test were within established limits as determined by other techniques. Thus, the tensile test which is commonly used to measure the mechanical parameters of engineering materials, can also be employed to measure the texture of fried potato crusts. This may allow for an efficient means of obtaining indices of french fry quality.

4.2 INTRODUCTION

The potato is the world's major food crop grown in the greatest quantities (Schoorl and Holt, 1983). Recent trends in the worldwide consumption of potatoes show that french fries are becoming increasingly popular (Anon, 1988). In fact, Talburt *et al.* (1987a) stated that the production of frozen french fried potatoes has exceeded an annual value of one billion dollars. In Manitoba, frozen french fry exports account for nearly 80% of all processed potato products, and contribute up to 140 million dollars in revenue (Manitoba Agriculture, 1998). In spite of the magnitude of potato production and its economic importance, the potato processing industry has had problems in the evaluation and control of french fry texture (Ross and Porter, 1971).

There are many variables encountered in potato processing. Source, variety, storage conditions, and processing conditions all affect the texture of french fries (Ross and Porter, 1971). The major method of texture evaluation performed on french fries has been sensory evaluation. Sensory evaluation of a finished product is very labour intensive; it is considered by food processors to be an inefficient method of texture evaluation for quality control (Finney 1969; Ross and Porter, 1966).

Many attempts have been made in the past to develop a replacement for the sensory evaluation of food products (Ross and Porter, 1966). There have been many instrumental methods used to define the texture of fruits and vegetables (Bourne, 1969; Bourne, 1972; deMan, 1969). However, these instrumental methods have mostly been empirical in nature and the effectiveness of empirical measurements has been questioned in the literature

(Bourne, 1982; Bourne, 1994). In contrast, Mohsenin (1970) has stated the usefulness and effectiveness of applying an objective, yet, fundamental engineering approach to the evaluation and measurement of the mechanical attributes of texture in food materials.

With respect to materials testing in the discipline of engineering, there are many fundamental parameters that characterize the mechanical properties of materials (Beer and Johnston, 1992). These fundamental parameters include, fracture stress, fracture strain, elastic modulus, Poisson's ratio, and fracture toughness. Therefore it follows that these well-defined mechanical properties could be used to characterize textural parameters of food materials.

With regards to fracture toughness, a generalized theory of fracture mechanics (Andrews, 1974) characterizes the fracture properties of materials without limiting assumptions of linearity, elastic behaviour, and infinitesimal strain (Holt and School, 1983). This has practical application in determining the fracture properties of food materials since considerable plastic deformation can occur during fracture development (Fahloul and Scanlon, 1996). Some authors have demonstrated the applicability of the generalized theory of fracture mechanics to characterize failure phenomena in biological materials (Fahloul and Scanlon, 1996; Holt and School, 1983). Other authors have used Gurney's work area method to characterize fracture in biological materials (Jeronimidis, 1980; Khan, 1989; Vincent, 1982). Gurney's work area method makes assumptions based on any plastic deformation being confined to a small region contiguous with new crack surface area (Gurney and Hunt, 1967). It discounts global energy losses, which are part of the "toughness" value in the generalized linear fracture mechanics analysis method. Using

such techniques, full mechanical analyses have been performed on biological materials as a means of obtaining fundamental mechanical constants that describe the constitutive properties of the biological material. This study was an investigation in measuring the mechanical properties of the crust of a fried potato, and particular attention was given to measuring the mechanical property of fracture toughness. Mechanical properties could be used to quantify the many variables encountered in potato processing that are technologically important to the industry. As previously mentioned, source, variety, storage, and processing conditions all affect the texture of french fries. It would be beneficial if the effects of these parameters were efficiently quantified through the measurement of the mechanical properties of french fries. Those potatoes producing french fries not meeting the desired specifications at intake could be processed under different processing conditions so as to achieve the mechanical properties corresponding to those of high quality french fries so that maximum product quality could be attained.

4.3 METHODS AND MATERIALS- Fracture Mechanics Analysis

4.3.1 Potatoes

Potatoes of the cultivar Russet Burbank were used as the experimental material. The crop was obtained from a commercial processing crop grown on a site near Carberry, Manitoba. Potatoes delivered from commercial storage in June 1996 and January 1997 were stored at the Horticultural Storage Research facility at the University of Manitoba. The potatoes were held at 8 ± 1 C and at a minimum relative humidity of 90% until used for processing.

Potatoes obtained in June 1996 from commercial storage were used for preliminary work and potatoes obtained in January 1997 used for the experimental work

4.3.1.1 Potato Processing

Potatoes were processed in order to obtain enough specimens for the preliminary experiments performed. Approximately five usable (free of rot and bruising) slices were obtained from each tuber. The potato slices were randomly split into 3 groups and were processed with three fry times: 1, 2, and 10 minutes. Similarly, for the main experimental work, potatoes were processed in order to obtain enough specimens for each fry time chosen. The potatoes slices were randomly split into five groups and were processed with one of five fry times: 1, 2, 4, 7, and 10 minutes.

For both the preliminary work and the main experimental work, all tubers were removed from storage and peeled just prior to processing. Slices (slabs) of 10 mm thickness were sliced lengthwise off potatoes from the stem end to the bud end. These potato slabs were processed according to the procedure followed in the commercial potato processing industry as described by Agblor (1997). Immediately after blanching and drying (Agblor, 1997) the potato slabs were placed in a wire frying basket and fried for various lengths of time in a thermostat controlled deep fat fryer (Garland Model 80-03, Mississauga, ON) set at 185 ± 2 C. The frying oil was hydrogenated canola oil with the trade name of Crisco Professional Frying Oil (Procter and Gamble, Toronto, ON). The amount of potato slabs (approximately 300) fried for the preliminary and experimental work was obtained without needing to change the frying oil. After frying, adhering oil was

removed by agitating the wire basket. The fried potato slabs were placed on a metal tray in a single layer and frozen. For freezing, the trays were placed in a walk-in air freezer (Model WTD, Coldstream Refrigerator Mfg. Ltd, Winnipeg, MB) at -20 C. They were placed close to a fan to simulate conditions in a blast freezer (Agblor and Scanlon, 1998). The fried potato slabs were frozen overnight on trays and then transferred to pre-labeled ziploc freezer bags and stored at -20 C until needed.

4.3.2 Preliminary Experiments

4.3.2.1 Crust Removal

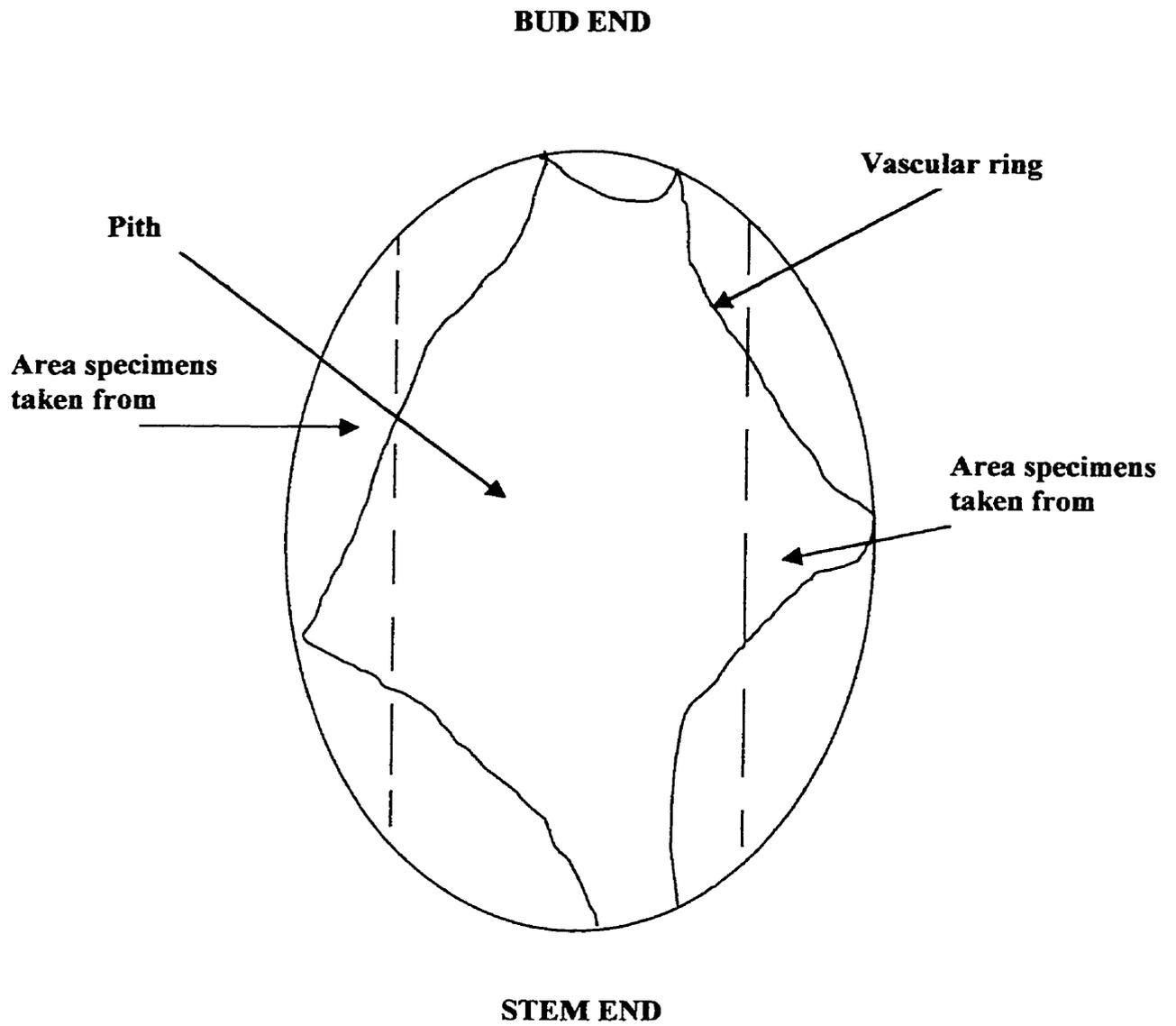
The crusts of the potato slabs were removed by slicing the frozen potato slabs with a Hobart slicer (Model 410, Hobart Manufacturing Co., Cincinnati, OH). Each batch of potato slabs fried for a certain time had a different crust thickness. The slicer was calibrated for each fry time by trial and error in order to cut off a crust slice from the slab with a minimum of inner core adhering to the crust. When the correct setting was determined for each fry time, it was marked on the slicer and used for obtaining subsequent crust slices. After the crust slices were obtained, they were placed on paper towels and put in plastic freezer bags to prevent moisture loss. The crust slices were allowed to thaw for ten minutes before being tested.

4.3.2.2 Specimen Preparation

Specimens were taken from outside of the vascular ring of the crust slices in order to limit incorporation of the pith in the specimen (Figure 1). The specimens obtained from

the crust slices were cut to a length of 80 mm and a width of 10 mm with a single blade. The dimensions chosen were such that they complied with those recommended by ASTM-E8-93 (ASTM, 1993) for tensile testing of metals since there is no standardized method available for the testing of biological materials. The thickness of the specimens was dependent upon their fry time, and was measured with a set of digital calipers. Ten specimens for each fry time were used to generate the values of average thickness.

FIGURE 1. SCHEMATIC DIAGRAM OF SPECIMEN LOCATIONS WITHIN THE TUBER



4.3.2.3 Testing of Specimens

All preliminary work was performed on the Ottawa Texture Measuring System (OTMS) equipped with a 25lb (110N) load cell (Canners Machinery, Simcoe, ON). The specimens were tested in tension with a crosshead speed of 22 mm min⁻¹. All testing was performed at room temperature.

Load-deformation curves were generated and analysed to obtain the elastic modulus, fracture stress, and fracture strain of the 1, 2, and 10 minute fried potato crusts. The specimens obtained from the 1, 2 and 10 minute fried potato slabs were attached to the aluminum end plates with cyanoacrylate adhesive (Viachem, St. Laurent, PQ) and allowed to set for 1 minute before testing was performed. The order of testing was randomized over the 30 specimens tested (ten replicates of each fry time).

The fried potato crust specimens from the 2 minute fry time were also tested for isotropicity. These test specimens were obtained from cutting crust pieces in both lateral and longitudinal orientations from adjacent faces of two fried potato slabs. The test specimens obtained from cutting in the lateral direction were taken across the middle of the crust from the fried potato slab. It should be noted that taking a lateral test specimen across the middle of the crust from the fried potato slab was the only way to obtain a specimen with a suitable gauge length. The longitudinal specimens were obtained from an area mainly outside of the vascular ring. It was believed that testing specimens cut from adjacent faces would allow for the isotropicity or anisotropicity of the potato tissue to manifest itself without being obscured by the inherent variability of the potato. Testing adjacent faces was likened to testing the same tissue. If differences in mechanical

properties were noted, they would be assumed to be due to an orientation effect rather than the natural variability present in the potato. Specimens were also cut in the lateral and longitudinal orientation from the opposite faces of these adjacent potato slabs. It was thought that there would be greater variability between tissue specimens taken from opposite faces than adjacent faces. Therefore four different situations were examined: ten adjacent/longitudinally cut specimens were tested, ten adjacent/laterally cut specimens were tested, ten opposite/longitudinally cut specimens were tested, and ten opposite/laterally cut specimens were tested. Testing was randomized over all 40 of these specimens. Load-deformation curves were generated and analysed to ascertain if there was a difference in the elastic modulus, fracture strength and fracture strain of the specimens made from different orientations and positions.

Measurements of Poisson's ratio were performed only on potato specimens fried for 2 minutes. To obtain the Poisson's ratio, a travelling microscope was used. A grid was drawn on the specimen with a marker before it was glued to the aluminum end plates of the OTMS for tensile testing. The initial dimensions of the grid were measured before the strip was deformed. The dimensions of the grid after deformation were measured within 45 s of application of the tensile load that created a given strain level. Different gluing orientations were examined to see their effect on the Poisson's ratio. Four different orientations were examined: 1) crust side glued to the end plates with the grid drawn on the core side, 2) core side glued to the end plates with the grid drawn on the crust, 3) core side glued to the end plates with the grid drawn on the core, and 4) the crust side glued to the end plates with the grid drawn on the crust. The specimens in all orientations were

subjected to a 10% strain level. The amount of replicates for each orientation and strain level ranged from 5 to 10 and testing was fully randomized.

4.3.3 Experimental Work

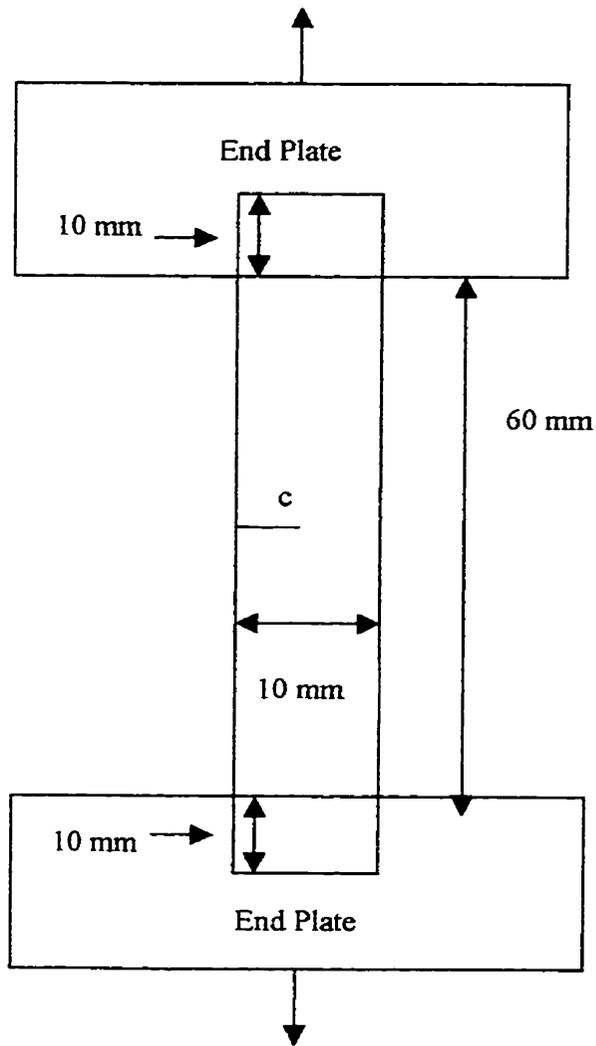
4.3.3.1 Crust Removal

Performed as described in Section 4.3.2.1

4.3.3.2 Specimen Preparation

Performed as described in Section 4.3.2.2. The thickness of the specimens was dependent upon their fry time, and was measured with a set of digital calipers. For each fry time 25 specimens were used to generate the values of average thickness. Single notches (i.e. cracks) cut into the side of the specimens were used in order to obtain fracture toughness values (Figure 2). The notch lengths (i.e. cracks) cut into the specimens were either 0, 2, 4, 6, or 8 mm.

FIGURE 2. DIMENSIONS OF FRIED POTATO CRUST SPECIMENS USED IN
TENSILE TEST (Note c = crack length experimentally cut in)



4.3.3.3 Testing of Specimens

Specimens were subjected to tensile forces on a Lloyd L1000 universal testing machine equipped with a 20 N load cell (Lloyd Instruments Ltd, Fareham, England). A crosshead speed of 1 mm min^{-1} was used for testing. All testing was performed at room temperature.

The specimens were attached to the aluminum end plates with cyanoacrylate adhesive and allowed to set for 1 minute before testing was performed. Load-deformation curves were recorded.

The effect of gluing orientation was examined by gluing the specimens to the end plates with either the core side or the crust side. For each fry time used, there were five notches of different lengths (i.e. crack lengths) cut into the specimen. Therefore five crack lengths were associated with the fried potato specimens. Each fry time with a specific crack length was replicated five times in completely random order. Therefore there were 125 load-deformation curves generated.

4.3.3.4 Light Microscopy

Light microscopy was performed on the fried potato specimens in order to qualitatively study the structure of the fried potato crust and see the effect of frying time on its structure. Also, light microscopy was also used to qualitatively deduce a value for Poisson's ratio of the fried potato crust. Potatoes were processed with the protocol previously stated (Section 4.3.1.1). Only the 1, 2, and 7 minute fry times were examined microscopically. Also, light microscopy was used to qualitatively examine the structure of

cork. This was done because the qualitative deduction of a value for the Poisson's ratio of fried potato crust involved comparison of the structure of fried potato crust and cork, which is also a cellular material with closed cells (Rosa and Fortes, 1988).

The preparation of the fried potato tissues and cork tissue involved fixation, dehydration, and resin embedding. These steps were carried out in capped glass vials at room temperature, unless otherwise stated.

The fried potato and cork issue samples were fixed in 3% glutaraldehyde (Sigma Chemicals, St. Louis, MO) in 0.025 M potassium phosphate (Sigma Chemicals, St. Louis, MO) buffer, pH 6.8 for 6 hours, then overnight at 4 C. They were washed several (3-4) times with 0.025 M potassium phosphate buffer, pH 6.8, and postfixed in 2% osmium tetroxide (Sigma Chemicals, St. Louis, MO) in 0.025 M potassium phosphate buffer, pH 6.8 for 4 hours. The fried potato and cork tissue samples were then washed with distilled deionized water three times for 20 minutes each time.

After fixation in glutaraldehyde/osmium tetroxide, fried potato tissue samples were passed through a graded series of aqueous ethanol solutions (Sigma Chemicals, St. Louis, MO) 30%, 50%, 70%, 90%, 95% for 20 minutes each, followed by 3 passes in 100% (non-aqueous) ethanol for 10 minutes each.

The dehydrated fried potato and cork tissue samples were then transferred step-wise from 100% ethanol to propylene oxide, a reagent which facilitates infiltration of the tissue by Spurr's resin (Marivac Chemicals, Halifax, NS). The dehydrated fried potato and cork tissue samples were first passed through a series of solution containing increasing proportions of 100% propylene oxide (Sigma Chemicals, St. Louis, MO) to 100% ethanol.

The series was:

100% Propylene oxide: 100% Ethanol

1:3 - 30 minutes

1:1 - 30 minutes

3:1 - 30 minutes

100% propylene oxide - 3 times for 30 minutes.

The fried potato and cork tissue samples were then passed through a series of solutions containing increasing proportions of Spurr's resin:

Spurr's resin: 100% Propylene oxide.

1:3 - 1 hour

1:1 - 4 hours

3:1 - overnight

100% Spurr's – overnight for fried potato crust and over a week for the cork while being continuously rotated (3 changes of Spurr's resin). It should be noted the cork was left to infiltrate over a long period due to its highly suberized cells, thus penetration of the plastic resin took longer.

The samples were then poured into 44 mm diameter aluminum weighing dishes (Fisher, Edmonton, AB), and the samples were distributed evenly in the bottom of the dish using a single-hair brush. These dishes were placed in an oven (Herhalser Hauptstabe 219 A-1171 Wien, Austria) at 70 C and left overnight to polymerize, resulting in a hard plastic disc containing the embedded fried potato and cork tissue samples.

The discs were removed from the aluminium dishes, and the embedded fried potato and cork tissue samples were cut from the plastic discs with a small hand saw. The embedded fried potato tissue samples were then mounted onto Spurr capsules with 5-minute epoxy resin (Lapage, Brampton, ON).

Prior to sectioning, the mounted samples were trimmed by hand with a razor blade such that the capsule had a trapezoidal face. The fried potato and cork tissue sections were cut on a Porter-Blum JB-4 microtome (Hartford, CT) with a glass knife; 2 μm sections seemed to be the ideal thickness. Sections were cut five at a time with a wet knife. It must be noted that for the fried potato crust specimens, the orientation of the crust plane to the microtome blade was such that it produced sections of the orientation the same as if one had a microscope looking at the crust while performing the tensile test. With respect to the cork specimens, radial, axial and tangential sections were taken relative to the longitudinal axis of the cork. The orientation of the tangential section of cork was of the same orientation as if one had a microscope looking at the cork if it was being subjected to a tensile test. All of the sections were transferred from the surface of the water in the wet knife to a drop of distilled, deionized water on a gelatin-coated glass slide. The slides were dried on a hot plate (at 65 C) under xylene vapour.

Crystal violet stain (Sigma Chemicals, St. Louis, MO) was used to outline basic morphology of the fried potato and cork tissue samples. The crystal violet stain is a basic, cationic dye which binds to acidic groups (Pease, 1964). Crystal violet stain was made by dissolving 2 g crystal violet in 20 mL ethanol and mixing with 0.8 g ammonium oxalate (Sigma Chemicals, St. Louis, MO) dissolved in distilled water (Gerhardt *et al.*, 1981). The

stain was filtered twice through Whatman #1 filter paper (Fisher, Edmonton, AB) and dispensed onto slide-mounted sections through a 0.45 μm filter. Specimens were stained for 45 seconds on a slide warmer at 65 C, and rinsed under running distilled water to remove excess stain. Slides were dried with a stream of filtered air, and mounted in 70% sucrose. The cytoplasm stains violet; good contrast is provided.

All sections were viewed on a Nikon Optiphot (Chiyoda-Ku, Tokyo, Japan) compound light microscope. Black and white photographs were produced on Kodak TMAX film, and printed on Kodak glossy photographic paper.

4.4 RESULTS AND DISCUSSION

4.4.1 Preliminary Work

The preliminary work was performed on the Ottawa Texture Measuring System (OTMS) with a crosshead speed of 22mm min⁻¹. The original load-deformation curves were used to generate values for the fracture stress, fracture strain, and elastic modulus of the crusts of the potato slabs fried for 1, 2, and 10 minutes. These values were calculated on the basis of engineering stress and engineering strain. Engineering stress (σ_0) refers to the measured load divided by the cross-sectional area of the specimen which is perpendicular to the applied load. Engineering strain (ϵ_0) refers to the measured deformation divided by the original gauge length of the specimen. The average (\pm standard deviation) for the thickness of the 1, 2, and 10 minute fry times were 0.85 (0.213), 1.11 (0.311), and 1.95(0.441) mm, respectively. The thickness of the crust increased with increased frying time. This fact is corroborated by the work of Dupont *et al.* (1992) and

Rice and Gamble (1989) in which it was stated that the growth of the crust corresponds with a major increase in oil content resulting from increased exposure to the frying medium.

4.4.1.1 Determination of Mechanical Properties

4.4.1.1.1 Determination of Fracture Stress, Fracture Strain, and Elastic Modulus

The fracture stress and fracture strain values were taken from the point of the load-deformation curve where fracture was observed to occur. The elastic modulus values were obtained from the load-deformation curves from the initial linear elastic region, which was on average in the 1-5% strain level. The first three rows of Table 1 show these values. It was observed that as frying time increased the fracture stress appears to have increased although the results do not conclusively indicate this. The elastic modulus of the crust increased while the fracture strain decreased as fry time increased.

Dupont *et al.* (1992) indicated that in their experiments as frying time increased the elastic modulus and fracture stress increased, while the deformation at fracture decreased. Dupont *et al.* (1992) obtained the elastic modulus values using a three point bending test of whole french fries. French fries with a frying time of 2 and 7 minutes had elastic modulus values of 0.740 and 3.2 kNm^{-2} , respectively. Dupont *et al.* (1992) obtained the fracture stress values using the Charpy pendulum test method. The fracture stress values of the 2 minute and 7 minute fried french fries were 44.2 and 142.6 kNm^{-2} , respectively. The values of fracture stress having a greater magnitude than the values for elastic modulus are most unusual (Atkins, 1987) and are probably due to the empirical test method used to

generate these values. This perplexing situation further signifies the need for standardized mechanical tests with a fundamental basis for obtaining texture measurements. The values of deformation at fracture obtained by Dupont *et al.* (1992) are not strain values and a direct comparison to the author's experimental fracture strain values is not applicable.

Atkins (1987) stated that the fracture stress and the elastic modulus of biological materials normally increase with decreasing moisture content. This fact is in accordance with the author's results and Dupont *et al.*'s (1992) results of elastic modulus values and fracture stress values. Also, Atkins (1987) noted that fracture is more readily achieved at lower moisture contents. This fact agrees with this author's experimental results and Dupont *et al.*'s (1992) findings of deformation at fracture being lower for potato specimens fried for longer fry times.

TABLE 1.**EFFECT OF FRYING TIME ON THE MECHANICAL PROPERTIES OF THE CRUST OF A FRIED POTATO SLAB (n = 10)**

Fry Time (minutes)	Fracture Stress (kNm ⁻²)	Elastic Modulus (MNm ⁻²)	Fracture Strain
1	116.02 ± 58.27	1.182 ± 0.741	0.075 ± 0.0167
2	74.99 ± 36.56	2.045 ± 0.398	0.040 ± 0.0142
10	99.18 ± 48.75	3.490 ± 1.544	0.050 ± 0.0149
1-2	110.07 ± 42.53	2.291 ± 0.241	0.078 ± 0.011
1-10	62.27 ± 22.23	1.953 ± 0.0675	0.041 ± 0.016
2-10	124.75 ± 48.11	2.230 ± 0.409	0.061 ± 0.011

testing speed was 22 mm min⁻¹

4.4.1.1.2 Contribution of the Crust and Core to the Elastic Modulus

The effect of core remaining on the crust was examined. In order to treat the french fry as a true composite material the crust should have mechanical properties independent of the core material and correspondingly the core should have mechanical properties independent of the crust. In order to determine the contribution of the crust and core to the elastic modulus, one minute and two minute fried potato slabs were sliced to the thickness of the crust of a 10 minute fried potato slab with the aim that there would be core remaining on the specimen. The results are shown in Table 1. This experimental treatment is indicated by 1-2, 1-10, 2-10 fry time denotation; 1-2 implies that a potato slab fried for 1 minute was sliced to the thickness of the crust of a potato slab fried for 2

minutes, therefore extra core would be present on the crust. There is no difference between the elastic modulus values for the 1 minute, and both the 1-2 minute and 1-10 minute specimens. Additionally, there is no difference between the elastic modulus values of the 2 minute and the 2-10 minute specimens. From these results (Table 1) it was determined that there was no effect of the core on the elastic modulus of the crust.

4.4.1.1.3 Determination of the Structural Orientation of the Fried Potato Crust

The structural orientation of the crust of the two minute fried potato slabs was examined. Specimens of crust were taken from laterally and longitudinally cut sections of the fried potato. From examination of the values of the elastic modulus it was determined that the crust was isotropic (Table 2). The elastic modulus values of the adjacent lateral and adjacent longitudinal specimens are very close, 1.49 and 1.54 MNm⁻², respectively. Also, the elastic modulus values of the opposite lateral and opposite longitudinal specimens are similar in magnitude as well, 1.32 and 1.87 MNm⁻², respectively. This finding of isotropicity of the fried potato crust was supported by the work of Khan and Vincent (1993) in which it was stated that potato parenchyma is isotropic with no cellular orientation, but disagrees with the findings of Pang and Scanlon (1996).

TABLE 2.**THE EFFECT OF LATERAL AND LONGITUDINAL ORIENTATION ON THE ELASTIC MODULUS OF THE CRUST OF A 2 MINUTE FRIED POTATO SLAB (n = 10)**

Type of Section	Elastic Modulus (MNm ⁻²)
Adjacent Lateral	1.49 ± 0.767
Adjacent Longitudinal	1.54 ± 0.983
Opposite Lateral	1.32 ± 0.528
Opposite Longitudinal	1.87 ± 0.713

4.4.1.1.4 Poisson's Ratio

An attempt was made to obtain the value of the Poisson's ratio for the crust of the 2 minute fried potato slab. From Table 3, it can be seen that gluing orientation affects the Poisson's ratio. It was hypothesized that there was an uneven stress distribution that was caused by the manner in which the specimens were glued. The gluing orientation may have caused the applied load to be concentrated on the side of the specimen that was glued to the end plate. It was stated by Beer and Johnston (1992) that the elements in the immediate vicinity of the points of application of loads are subjected to very large stresses, while other elements external to the area of loading are unaffected. If an applied load is evenly distributed, the specimen will deform and remain straight without rotating. The hypothesis of an uneven stress distribution was verified in this author's experiments by the observation of bending or curving of the specimens towards the side of the specimen that was glued. In other words, upon looking at the specimen in tension, instead of viewing a

flat face, a curved (or U shaped) surface was seen. The effect of this uneven stress distribution on the Poisson's ratio was two-fold. With the uneven stress distribution all elements would not deform in the same manner and the strain distribution would not be uniform and the measured Poisson's ratio would not reflect the true material properties of the crust. Also, the curving of the specimen would cause a distortion of the dimensions of the grid being measured with the travelling microscope and this too would result in inaccurate measurement of the Poisson's ratio.

Nevertheless, it was established that there was an inherent error made by the experimenter in using inappropriate testing equipment. Ideally the specimens should have been clamped to the end plates eliminating the uneven stress distribution incurred upon gluing. Clamping the specimens to the end plates was investigated. However the nature of the crust made it impossible to clamp the specimen without cutting into the sample and ruining it prior to testing. Therefore qualitative assessment of the Poisson's ratio was attempted due to inconclusive quantitative results. Microscopy was performed on the 1, 2 and 7 minute fried potato slabs.

TABLE 3.**THE EFFECT OF GLUING ORIENTATION ON THE POISSON'S RATIO OF THE CRUST OF A 2 MINUTE FRIED POTATO SLAB**

Gluing Orientation	10 % Strain Level
Crust glued-core measured	1.189 ± 1.467 ^a
Core glued-crust measured	0.552 ± 0.185 ^c
Crust glued-crust measured	1.125 ± 0.391 ^b
Core glued-core measured	0.826 ± 0.298 ^d

^a sample size (n) = 8

^b n = 10

^c n = 6

^d n = 5

Reeve and Neel (1960) investigated the microscopic structure of potato chips and stated that the microscopic structure of french fries is very similar to that of potato chips. The microscopic appearance of a french fried potato is such that the cells are shrunken and the cellulosic walls are wrinkled and convoluted around the dried starch cell content. The cell walls are not ruptured upon deep-fat frying (Reeve and Neel, 1960).

By viewing the photomicrographs of the 1, 2, and 7 minute fried potato crusts in Figures 3, 4, and 5, respectively, it was observed that as the frying time increased the degree of dehydration increased and the oil content increased. This can be seen in the photomicrographs where the 7 minute fried potato crust has a greater amount of black and

gray areas compared to the 1 and 2 minute fried potato crusts. This can be explained by the fact that osmium tetroxide stains lipid black (Reeve and Neel, 1960).

It was noted that the cells of the crust had a hexagonal appearance. Interestingly, the microstructure of the cells in the crust was very similar to the microstructure of cork. In the literature cork has been described as a cellular material with closed hexagonal cells (Rosa and Fortes, 1988). Therefore it was hypothesized that the crust of the fried potato material was similar to that of cork. Fortes and Nogueira (1989) presented a scanning microscope image of a tangential section of cork. Likewise, Figure 6 shows a photomicrograph of cork of a tangential section of cork taken as a section perpendicular to the radial direction of cork. Both of these images show a structure very similar to that of the fried potato crust. It was stated that compression or tension in both the axial or tangential direction (i.e. the non-radial direction) gives a Poisson's ratio of 0.5 for cork (Gibson *et al.*, 1981; Rosa and Fortes, 1988). It was therefore surmised that the Poisson's ratio of the fried potato crust, when subjected to tension as in the authors' experiments, would have a value of 0.5. It is acknowledged that this deduction may not be entirely accurate in that fried potato crust and cork are composed of different materials, and therefore differ in molecular structure. However, at an intermediate level, i.e., cellular level, the similarities between the cork and potato cells may warrant such a qualitative deduction.

FIGURE 3. PHOTOMICROGRAPH OF A SECTION OF A 1 MINUTE FRIED POTATO CRUST (MAG 214.5X)

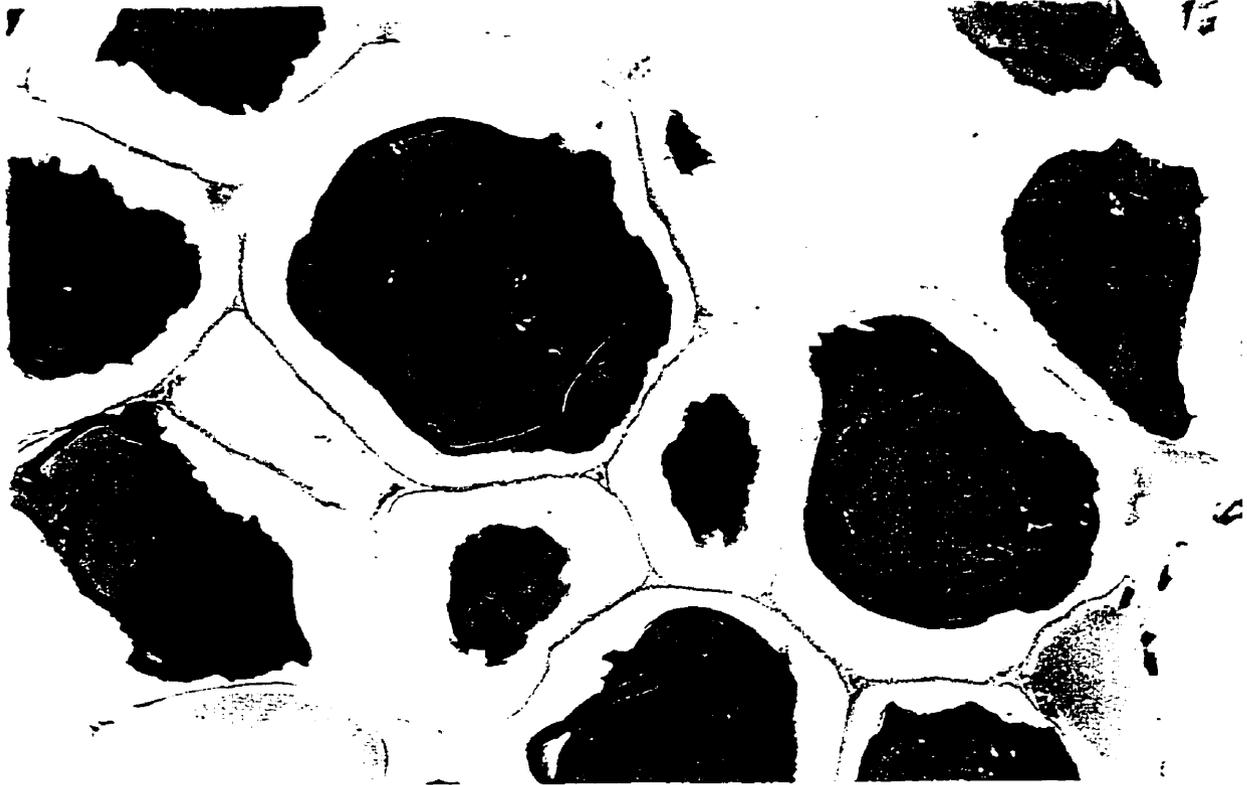


FIGURE 4. PHOTOMICROGRAPH OF A SECTION OF A 2 MINUTE FRIED POTATO CRUST (MAG 214.5X)



FIGURE 5. PHOTOMICROGRAPH OF A SECTION OF A 7 MINUTE FRIED POTATO CRUST (MAG 214.5X)

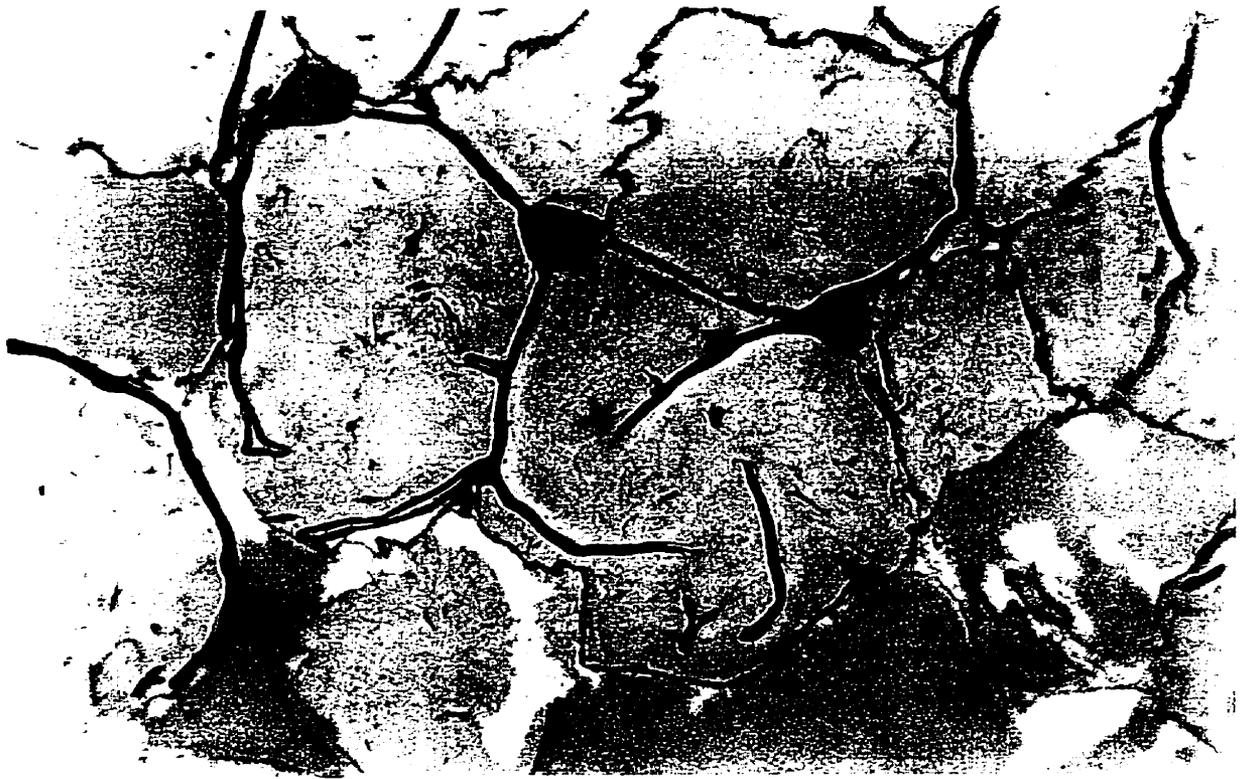


FIGURE 6. PHOTOMICROGRAPH OF A TANGENTIAL SECTION OF CORK
(MAG 214.5X)



4.4.2 Determination of the Mechanical Properties of the Fried Potato Crust

4.4.2.1 Stress-Strain Response

The main experimental work was performed on the Lloyd Instrument which employed a crosshead speed of 1 mm min^{-1} . The original load-deformation curves were converted into engineering stress-strain curves (see above). Both the stress and the strain were measured from points remote from the experimentally imposed crack (i.e. the notch cut into the sample) which the subscript 0 indicates (4.4.2.3) and are therefore calculable from the load-deformation curves (Andrews and Billington, 1976; Fahloul and Scanlon, 1996). Figure 7 is the mean ($n = 5$ for all fry times) stress-strain curve for all fry times without any cracks cut into the specimens (i.e. $c=0$ for all of the curves). The mean stress-strain curve for the specimens containing cracks/notches cut to different lengths for each fry time are shown in Figures 8 to 12. Error bars have been calculated with a 95% confidence interval ($n = 5$). The error bars are for the $c = 0$ curve at increments of 0.5% strain. The error bars for curves with cracks in them were considerably smaller. It should be noted that each curve was terminated when the crack was observed to propagate. Additionally, it should be stated that the previous figures (8-12) are not plotted on the same scale to prevent limiting the representation of the data for longer fry times to a small region. Also, the mechanical parameters of fracture stress, fracture strain and elastic modulus were obtained from the stress-strain curves of each individual potato crust fried for varying times with no experimental cracks (i.e. $c = 0$). It should be noted that the average thickness (\pm standard deviation) of the 1 minute, 2 minute, 4 minute, 7 minute,

and 10 minute fry times were 0.73 (0.18), 1.04 (0.26), 1.31 (0.35), 1.65 (0.45), 1.99 (0.48) mm, respectively.

FIGURE 7. MEAN ($n = 5$) STRESS-STRAIN CURVES FOR ALL FRY TIMES
WITHOUT ANY EXPERIMENTAL CRACK LENGTHS CUT INTO THE
SPECIMENS

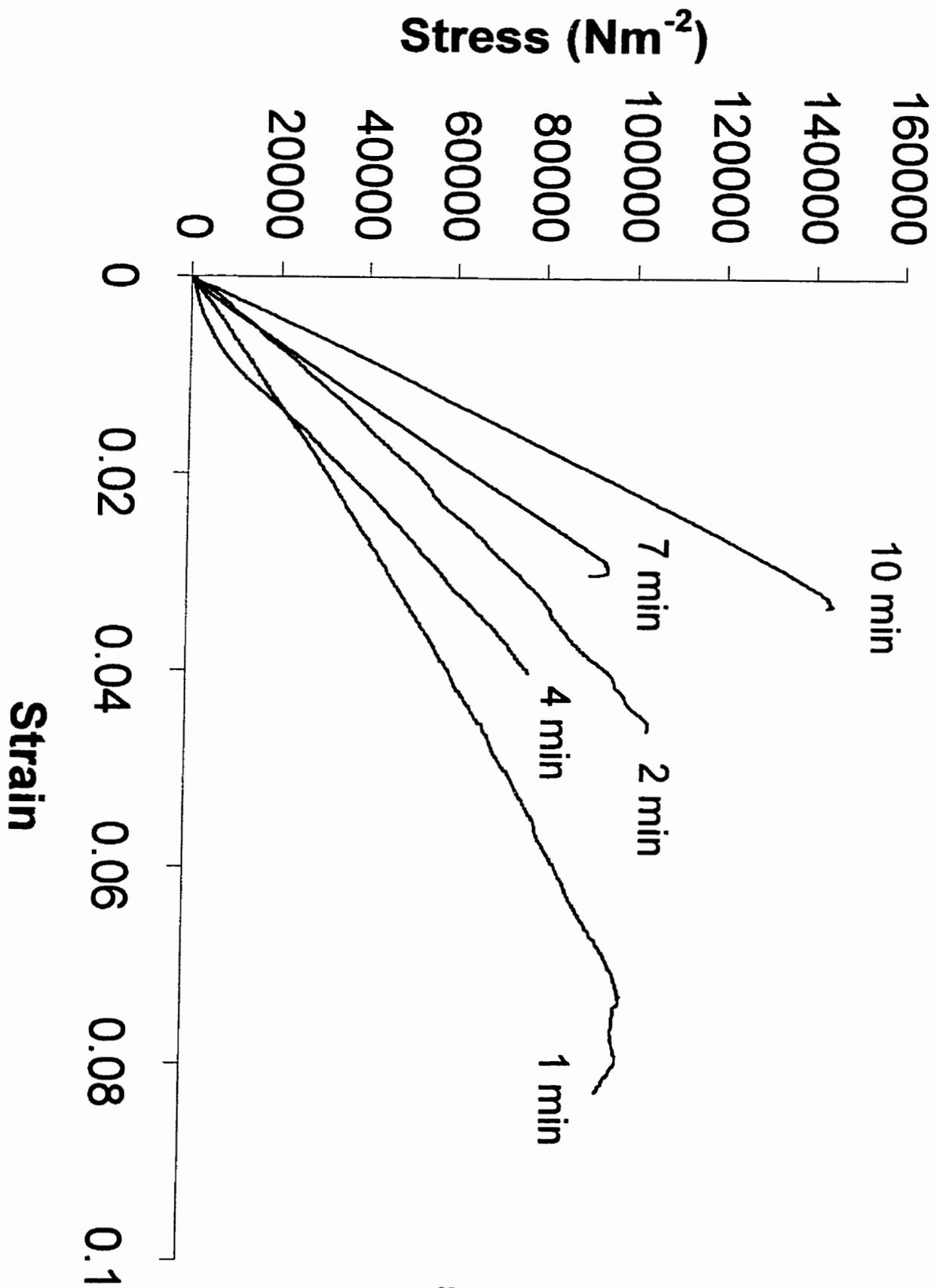


FIGURE 8. THE MEAN ($n = 5$) STRESS-STRAIN CURVES FOR 1 MINUTE FRIED POTATO CRUST SPECIMENS OF DIFFERENT CRACK LENGTHS
Error bars for curve $c = 0$ indicate 95% confidence interval.

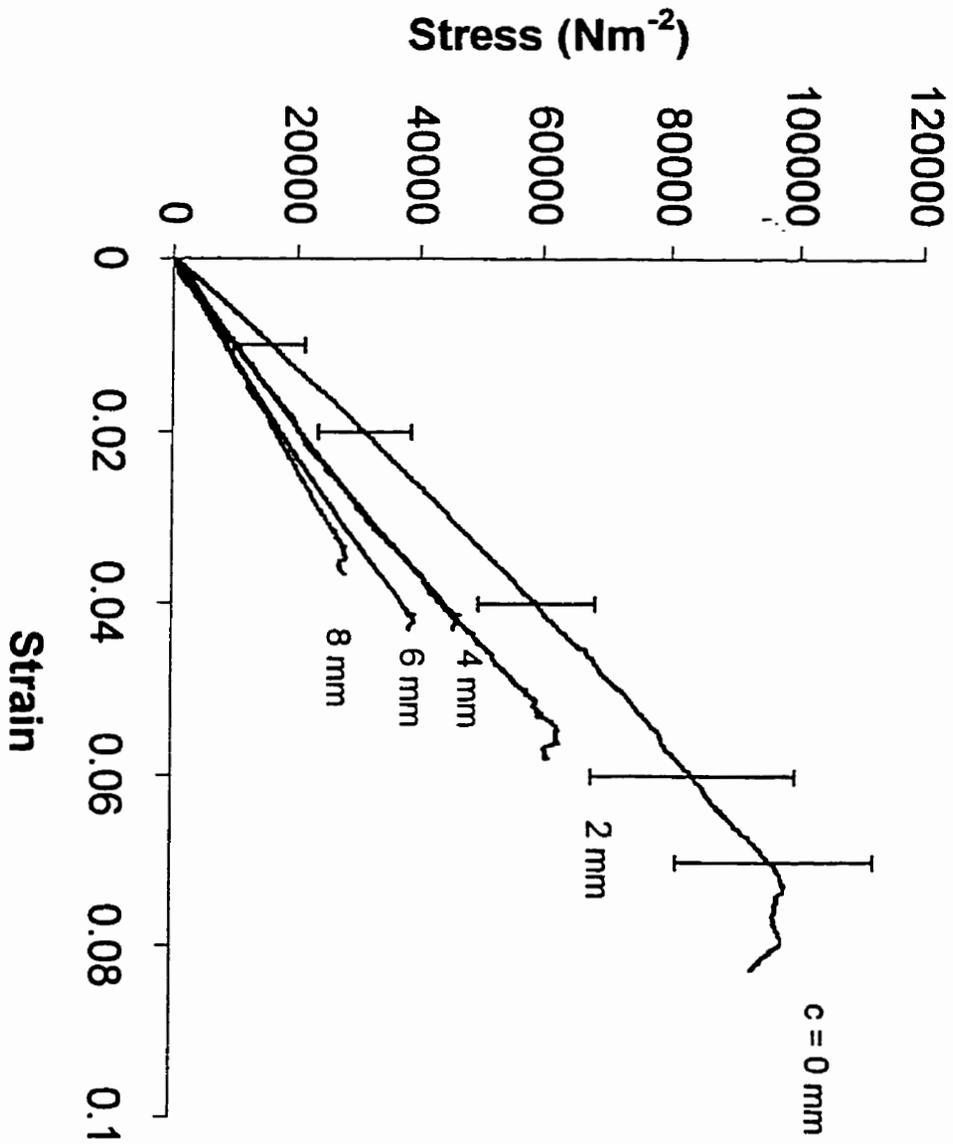


FIGURE 9. THE MEAN ($n = 5$) STRESS-STRAIN CURVES FOR 2 MINUTE FRIED POTATO CRUST SPECIMENS OF DIFFERENT CRACK LENGTHS
Error bars for curve $c = 0$ indicate 95% confidence interval.

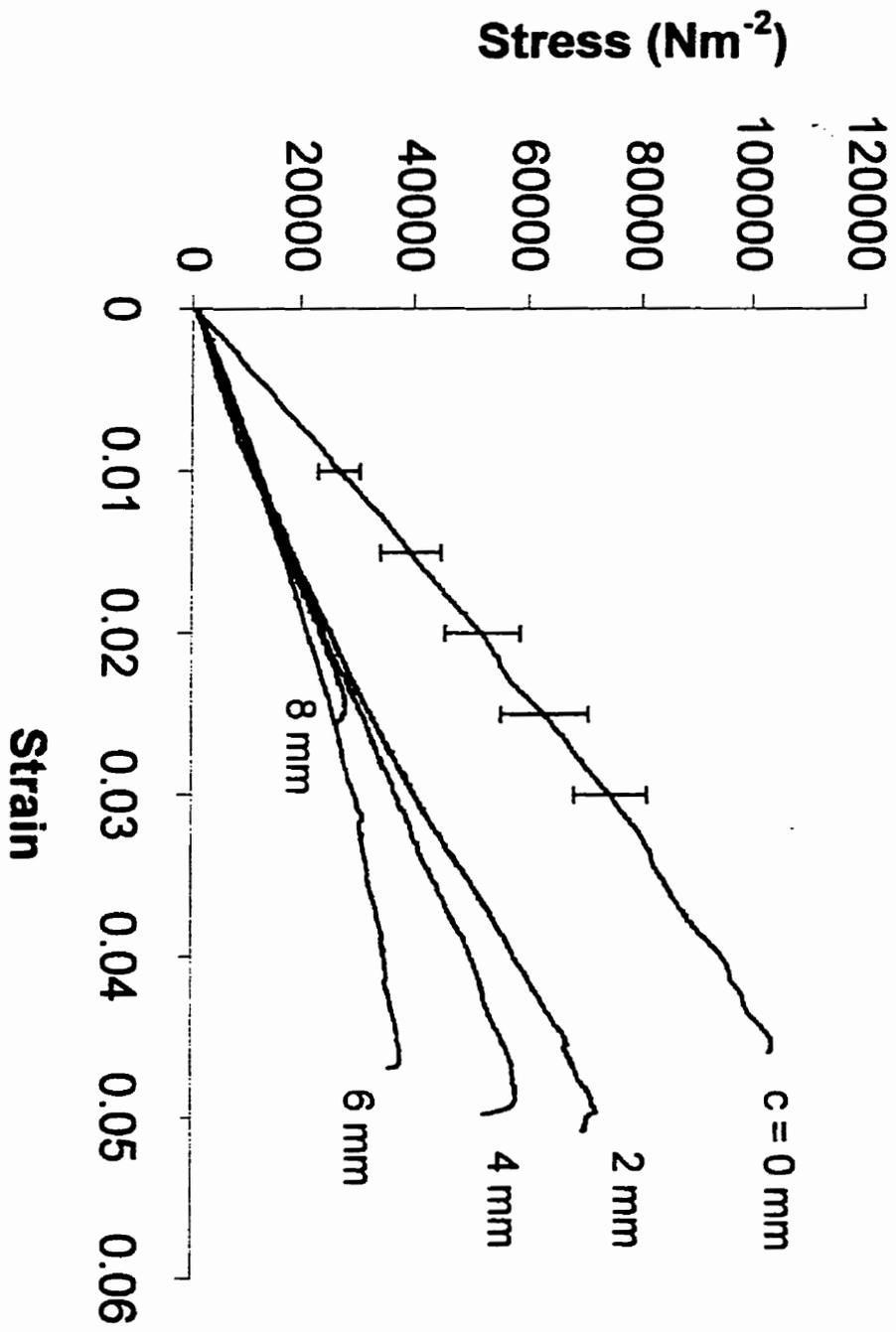


FIGURE 10. THE MEAN ($n = 5$) STRESS-STRAIN CURVES FOR 4 MINUTE FRIED POTATO CRUST SPECIMENS OF DIFFERENT CRACK LENGTHS
Error bars for curve $c = 0$ indicate 95% confidence interval.

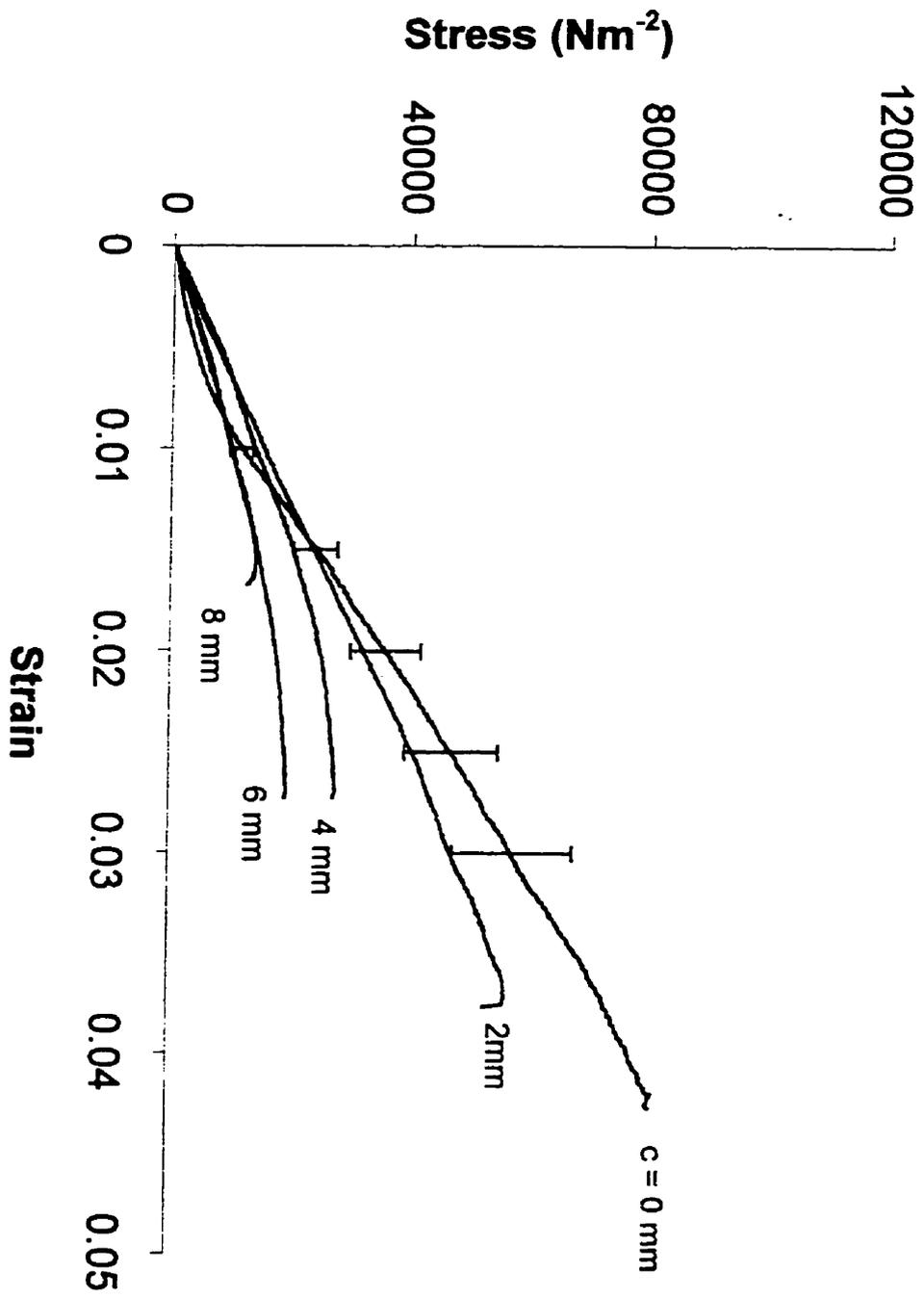


FIGURE 11. THE MEAN ($n = 5$) STRESS-STRAIN CURVES FOR 7 MINUTE FRIED POTATO CRUST SPECIMENS OF DIFFERENT CRACK LENGTHS
Error bars for curve $c = 0$ indicate 95% confidence interval.

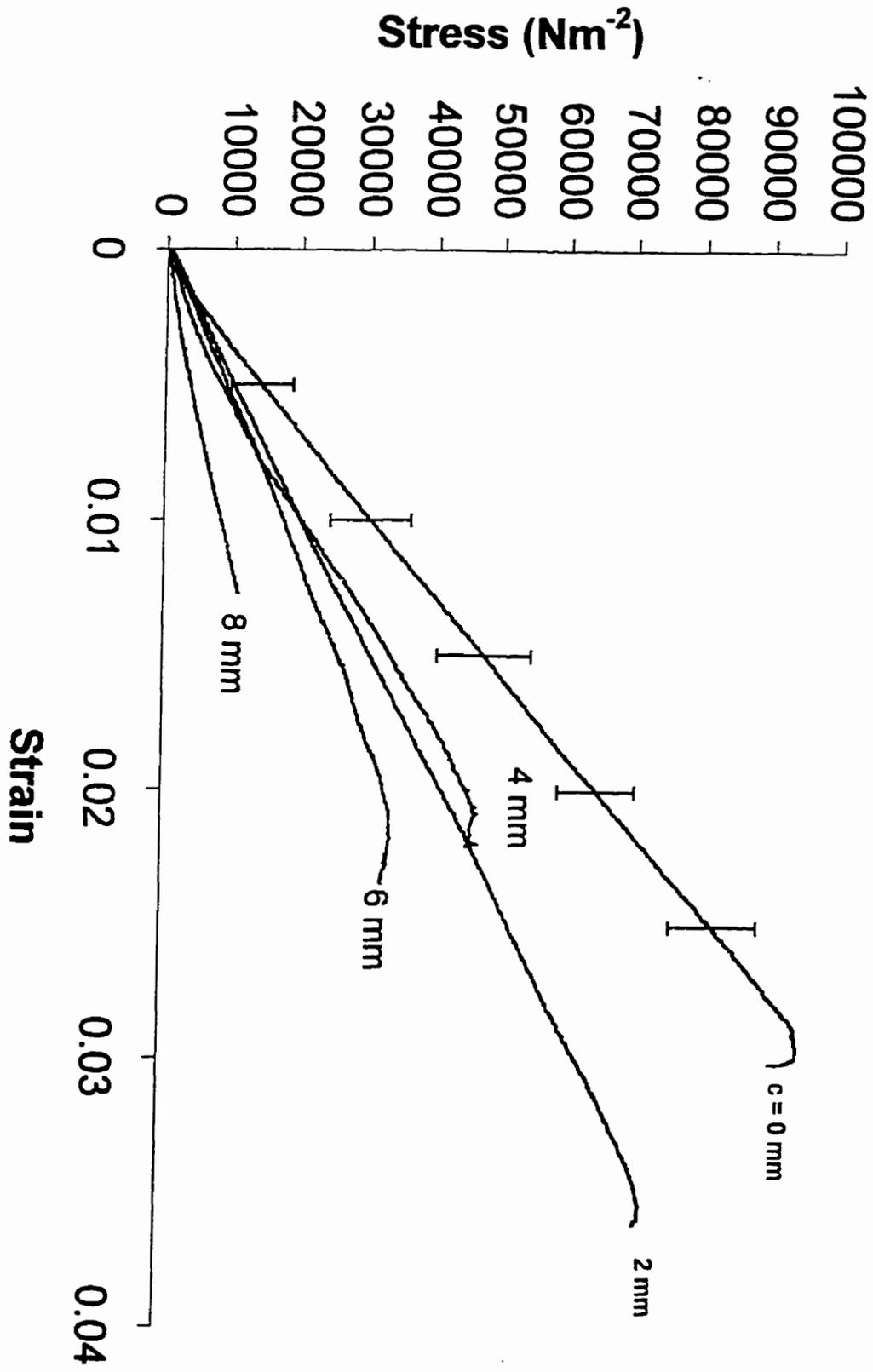
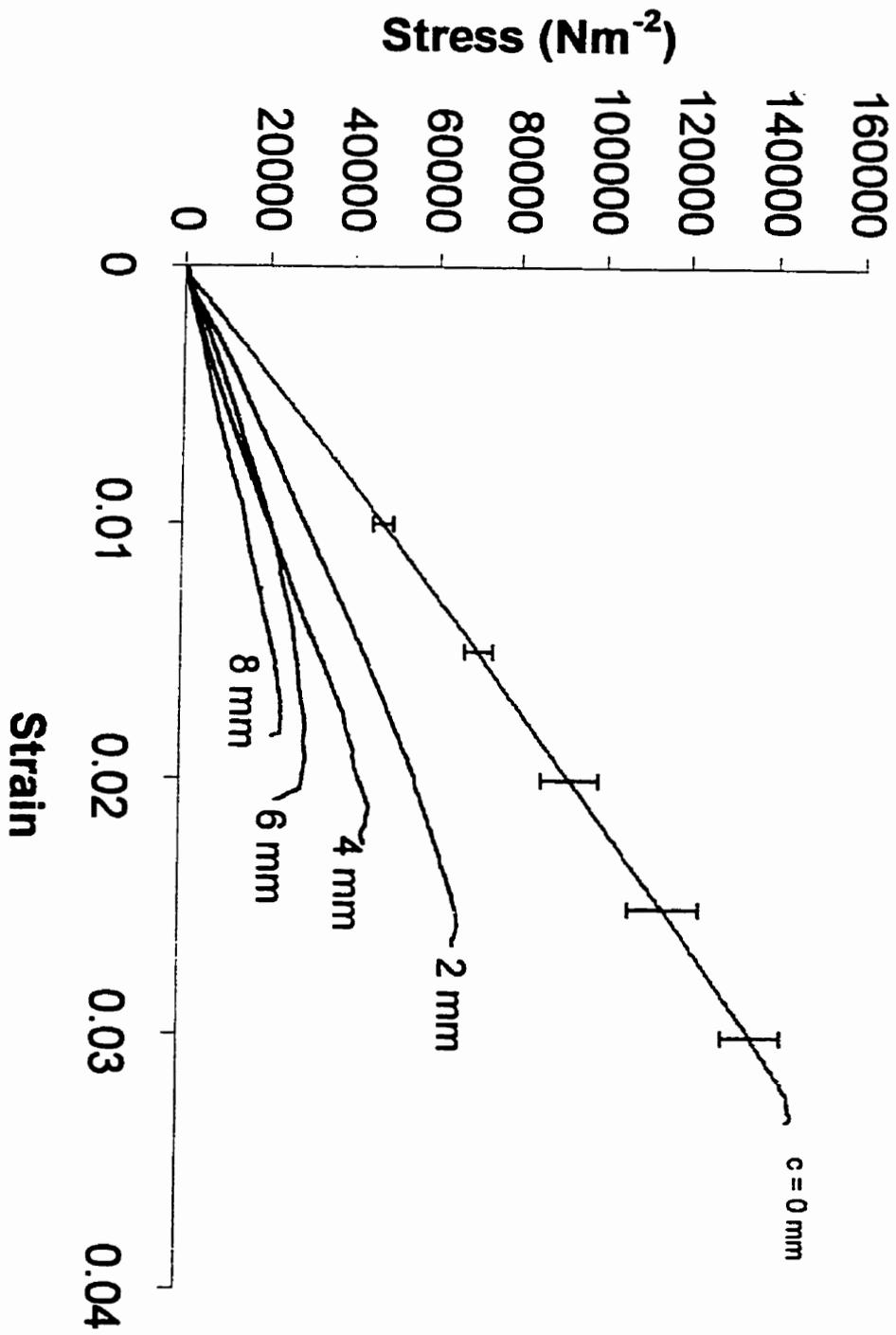


FIGURE 12. THE MEAN ($n = 5$) STRESS-STRAIN CURVES FOR 10 MINUTE FRIED POTATO CRUST SPECIMENS OF DIFFERENT CRACK LENGTHS Error bars for curve $c = 0$ indicate 95% confidence interval.



4.4.2.2 Determination of Fracture Stress, Fracture Strain and Elastic Modulus

The fracture stress and fracture strain values were taken from the point on each of the stress-strains curve where fracture was observed to occur. The elastic modulus values were obtained from each of the stress-strain curves from the initial linear elastic region, which was on average in the 1-4% strain level. Table 4 shows these values. Just as it was observed in the preliminary experiments, as frying time increased the elastic modulus of the crust increased. The fracture strain generally decreased as fry time increased. These results were anticipated by the author and are supported by the work of Dupont *et al.* (1992). A result unexpected by the author was the similarity in the magnitude of the results in Tables 1 and 4. The author expected a strain rate effect to be present and the values of Table 1 to be higher than the values of Table 4. Previous work performed by the author on a 3% agar gel indicated that strain rate significantly affects the mechanical properties of a viscoelastic material (Chapter 3). For a viscoelastic material, as the strain rate increases the elastic modulus increases in magnitude. The greater forces generated at higher deformation rates can be explained by slower strain rates allowing for relaxation and flow of the viscoelastic material (Munoz *et al.*, 1986). The fact that strain rate did not affect the mechanical properties of fried potato crust indicates that it may not be a viscoelastic material, rather an elasto-plastic material.

TABLE 4.

**EFFECT OF FRYING TIME ON THE MECHANICAL PROPERTIES
OF THE CRUST OF FRIED POTATO (n = 5)**

Fry Time (minutes)	Fracture Stress (kNm ⁻²)	Elastic Modulus (MNm ⁻²)	Fracture Strain
1	97.1 ± 26.74	1.41 ± 0.564	0.0790 ± 0.0176
2	103.4 ± 10.95	2.67 ± 0.534	0.0457 ± 0.0151
4	80.6 ± 17.02	2.00 ± 0.881	0.0419 ± 0.0105
7	94.2 ± 10.83	3.32 ± 0.812	0.0293 ± 0.008
10	144.0 ± 11.63	4.00 ± 0.746	0.0331 ± 0.001

testing speed was 1mm min⁻¹

4.4.2.3 Generalized Fracture Mechanics Theory

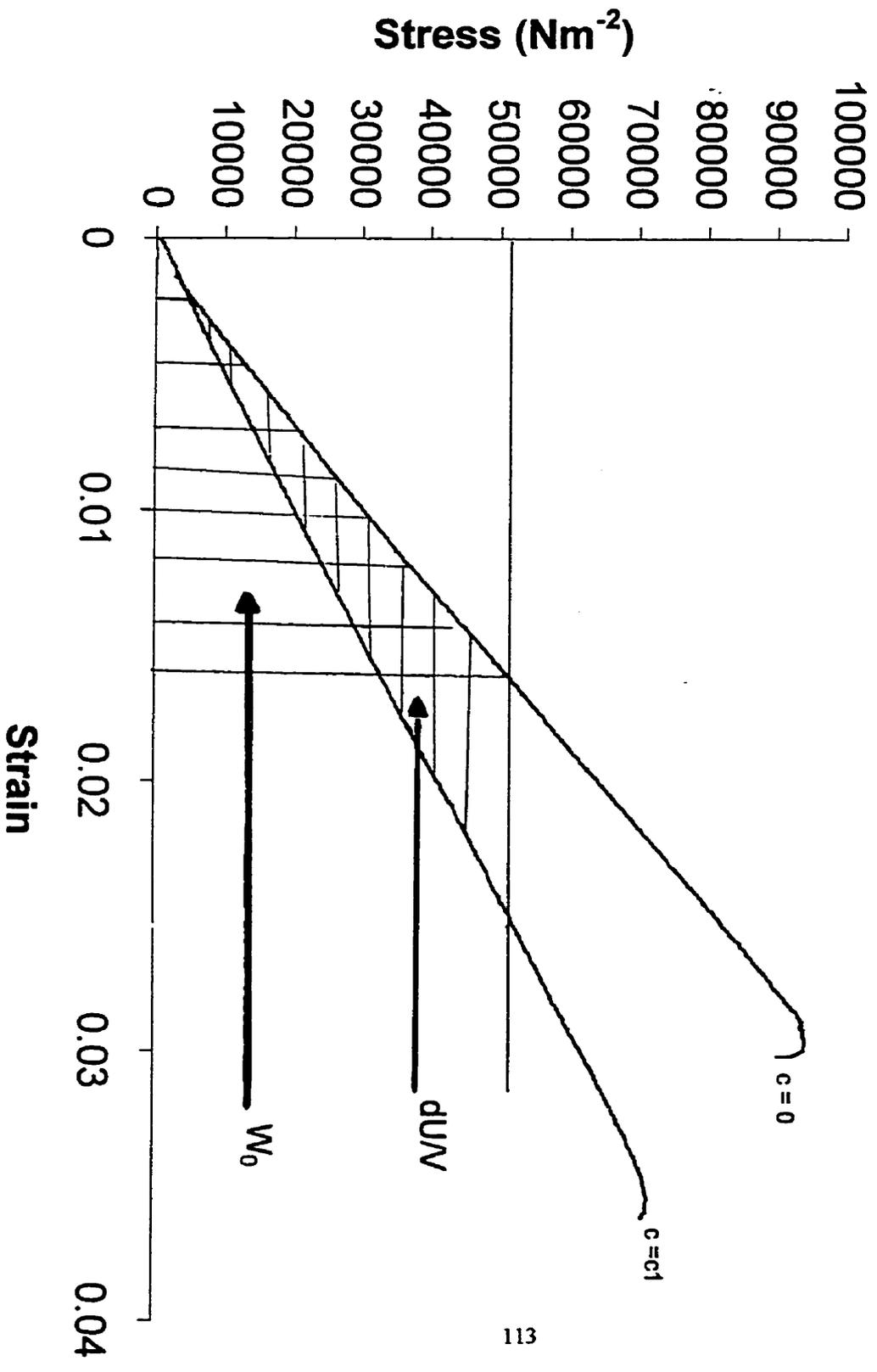
The generalized fracture mechanics theory (Andrews, 1974) gives the following equation for fracture propagation from an edge crack in a tensile specimen:

$$T = k_1(\epsilon_0)cW_{0c} \quad (1)$$

Where: T is the critical apparent energy release rate or “surface work”; k_1 is a dimensionless function of strain, ϵ_0 , measured at points remote from the crack; c is crack length; and W_{0c} is the input energy density (W_0) when crack propagation occurs (Fahloul and Scanlon, 1996). As stated by Fahloul and Scanlon (1996) both W_0 and ϵ_0 are defined by the intersection of a given stress with the stress-strain curve of the uncracked specimen ($c = 0$). Therefore the function k_1 can be determined as a function of the input energy density (W_0) or k_1 can be evaluated as a function of strain (Fahloul and Scanlon, 1996). This can be seen in Figure 13. Just as Fahloul and Scanlon (1996) determined the function k_1 as a function of the input energy density (W_0) for their study, k_1 was determined in the same manner for this study. The input energy density (W_0) is associated with the

uncracked specimen. Figure 13 schematically shows the difference between the input energy density per unit volume (dU/V) of the uncracked specimen and the cracked specimen at a given stress or (input energy density) value. Upon evaluation of $k_I(W_0)$, the critical energy release rate may be obtained from the value W_{0c} where crack propagation occurs (Andrews and Bhatti, 1982; Fahloul and Scanlon, 1996).

FIGURE 13. SCHEMATIC DIAGRAM OF INPUT ENERGY DIFFERENCE (dU) AND THE INPUT ENERGY DENSITY (W_0) AT A CONSTANT STRESS VALUE



4.4.2.3.1 Evaluation of the Function $k_1(W_0)$

The total energy change in the system due to the propagation of a crack is described by the following equation

$$\frac{-dU}{dA} = k_1(W_0)cW_0 \quad (2)$$

Where: U is the total input energy into the specimen to propagate a crack at a constant stress and A is the crack area. The negative sign is used in the equation because the dU is referred to a specimen without a crack ($A_0 = 0$) so that it denotes the energy available within the normal specimen to create a crack or a unit of new crack area. Since $dA = 2h(dc)$, where h is the initial specimen thickness (2) can be expressed as:

$$\frac{-dU}{dc} = 2hk_1(W_0)cW_0 \quad (3)$$

A plot of $-dU/dc$ against c should be linear for a specific W_0 to give a series of straight lines extending through the origin with a slope of $2hk_1(W_0)W_0$. In order to obtain such a plot, values of dU and W_0 were obtained from the stress strain curve for each of the 1, 2, 4, 7, and 10 minute fried potato crusts, at different stresses (with a corresponding W_0 associated with the stress). Values of dU and W_0 for the 1 minute fried crust were obtained by taking stresses between 3.9 to 46.6 kNm^{-2} in increments of 3.9 kNm^{-2} . Values of dU and W_0 for the 2 minute fried crust were obtained by taking stresses between 4.8 to 57.9 kNm^{-2} in increments of 4.8 kNm^{-2} . Values of dU and W_0 for the 4 minute fried crust were obtained by taking stresses between 2.3 to 27.6 kNm^{-2} in increments of 2.3 kNm^{-2} . Values of dU and W_0 for the 7 minute fried crust were obtained by taking stresses between 3.8 to 46.6

kNm^{-2} in increments of 3.8 kNm^{-2} . Values of dU and W_0 for the 10 minute fried crust were obtained by taking stresses between 3.7 to 44.6 kNm^{-2} in increments of 3.7 kNm^{-2} . By using the trapezoidal numerical method for all of the crusts with different fry times, values of dU and W_0 could be calculated (Press *et al.*, 1986). Figures 14 through 18 show these plots. For clarity only five of the twelve input energy densities have been shown. It can be observed that, for all fry times, good linearity is apparent at larger energy densities. This may be due to the simple fact that at larger energy densities fewer experimental points were obtained because specimens with longer cracks had already fractured.

The function $k_1(W_0)$ had different properties for different fry times. These plots can be seen in Figures 19 - 23. For the 4, 7, and 10 minute fried potato crusts, a polynomial fit (order of 3) with a y-intercept of π (numerically, 3.14159) adequately characterized the function $k_1(W_0)$. For the 1 and 2 minute fried potato crusts, a polynomial fit (order of 2) with y-intercepts of 15.56 and 17.12, respectively characterized the function $k_1(W_0)$. The y-intercept was unforced for the 1 and 2 minute fried potato crusts and forced through π for the 4, 7, and 10 minute fried potato crusts because this treatment allowed for lines with the best r^2 values to be generated. It should be noted that for each fry time 4 combinations of polynomial fits were investigated. These fits involved: a polynomial fit (order of 2) with an unforced y-intercept, a polynomial fit (order of 2) with a y-intercept forced to π , a polynomial fit (order of 3) with an unforced y-intercept, and a polynomial fit (order of 3) with a y-intercept forced to π . Therefore it was believed the treatment of characterizing the data with the polynomial equation with the best r^2 value was the most suitable for analyzing the data. And such, when considering the 4, 7, and 10 minute fried potato crusts,

the function $k_1(W_0)$ tended towards the classical plane stress conditions value of π as W_0 approached a value of zero (Andrews and Billington, 1976; Fahloul and Scanlon, 1996; Griffith, 1921). In the intermediate region the material is in the elasto-plastic region, and when function $k_1(W_0)$ plateaus or becomes constant at greater input energy density, the material is in the plastic region (Andrews and Billington, 1976; Fahloul and Scanlon, 1996). An essentially constant value for k_1 at greater input energy densities was observed for all fry times except for the 4 minute fried potato crust. The function of $k_1(W_0)$ for the 4 minute fried potato crust had negative values at some input energy densities and was viewed as an anomaly.

FIGURE 14. TOTAL INPUT ENERGY CHANGE PER UNIT OF CRACK EXTENSION AS A FUNCTION OF CRACK LENGTH (c) AT DIFFERENT ENERGY DENSITY LEVELS FOR 1 MINUTE FRIED POTATO CRUST ■ = 1117.4, ▲ = 254.1, ● = 178.3, – = 144.3, ● = 62.2 (J m^{-3})

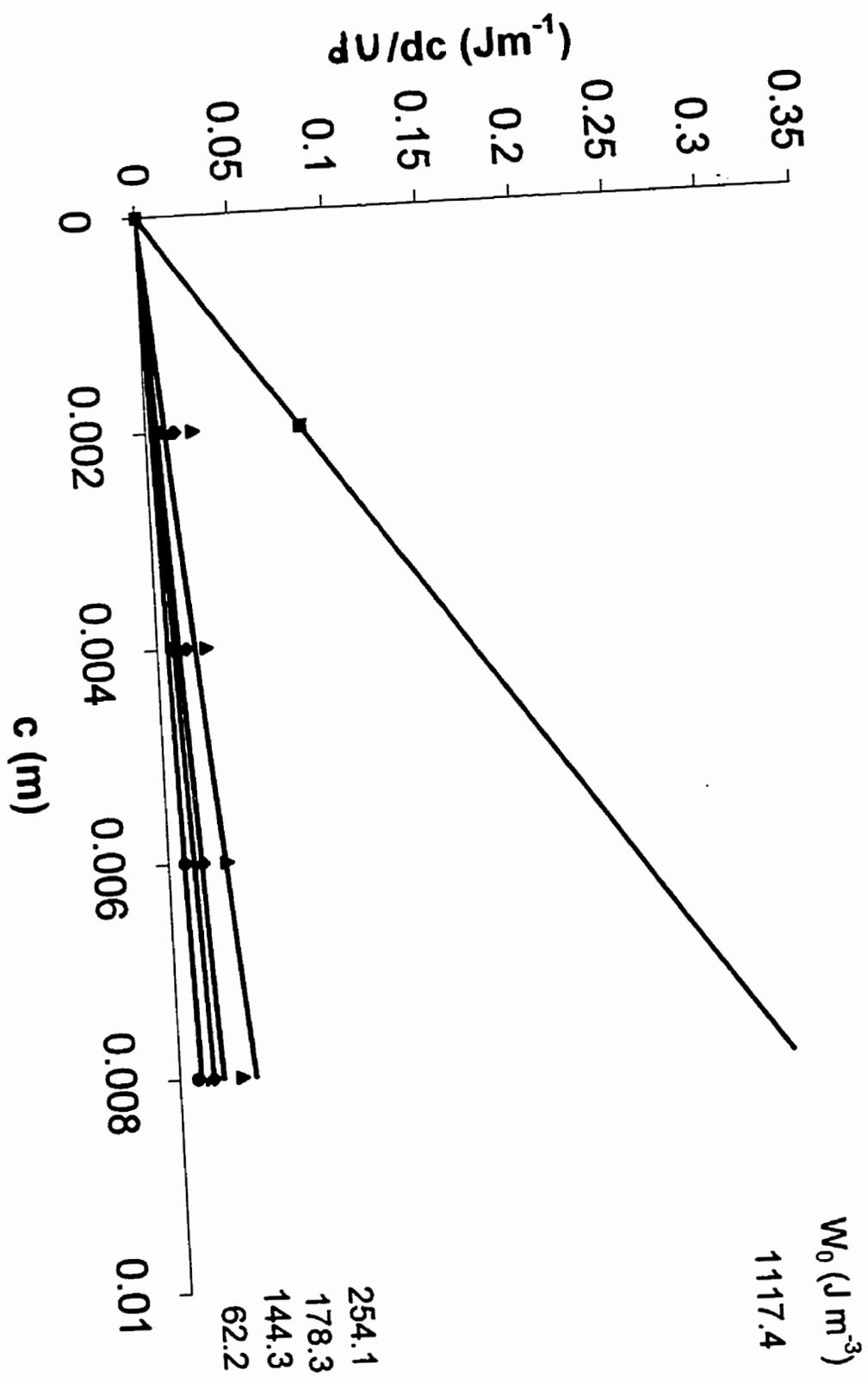


FIGURE 15. TOTAL INPUT ENERGY CHANGE PER UNIT OF CRACK EXTENSION AS A FUNCTION OF CRACK LENGTH (c) AT DIFFERENT ENERGY DENSITY LEVELS FOR 2 MINUTE FRIED POTATO CRUST ■ = 1668.0, ▲ = 704.6, ● = 561.5, - = 236.9, • = 101.5 (J m^{-3})

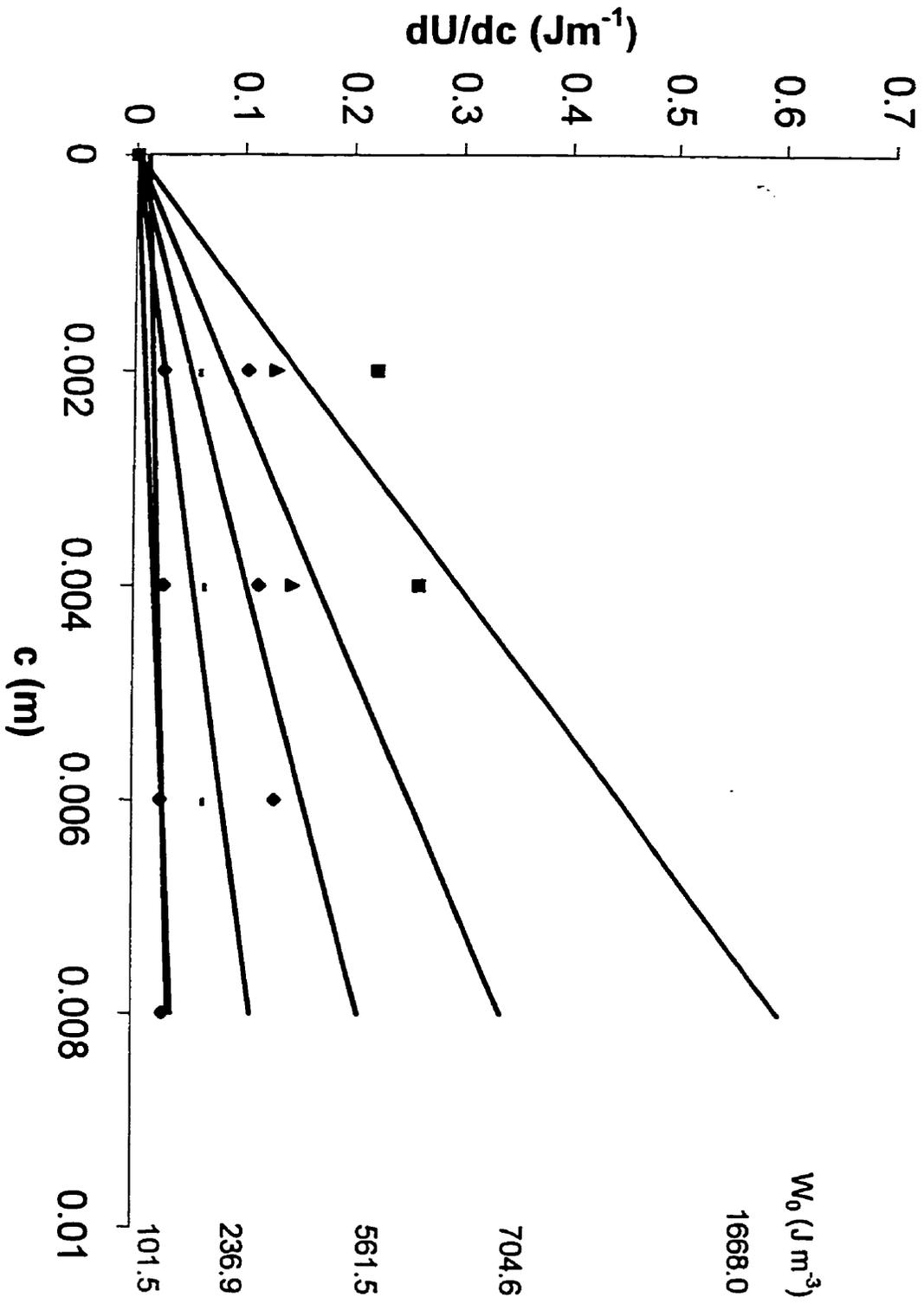


FIGURE 16. TOTAL INPUT ENERGY CHANGE PER UNIT OF CRACK EXTENSION AS A FUNCTION OF CRACK LENGTH (c) AT DIFFERENT ENERGY DENSITY LEVELS FOR 4 MINUTE FRIED POTATO CRUST ■ = 146.1, ▲ = 103.4, ◆ = 85.3, - = 56.1, ● = 44.4 (J m^{-3})

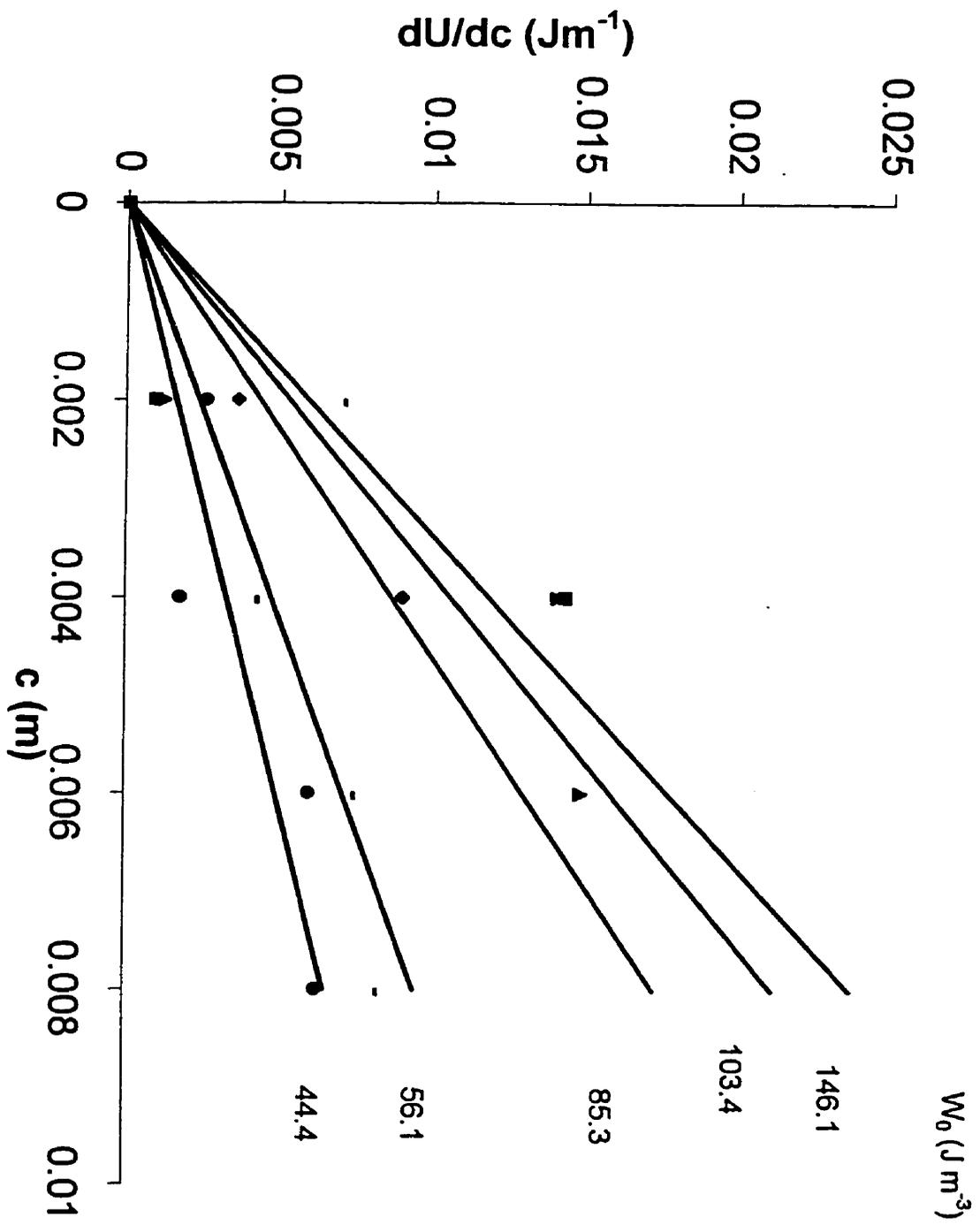


FIGURE 17. TOTAL INPUT ENERGY CHANGE PER UNIT OF CRACK EXTENSION AS A FUNCTION OF CRACK LENGTH (c) AT DIFFERENT ENERGY DENSITY LEVELS FOR 7 MINUTE FRIED POTATO CRUST ■ = 325.1, ▲ = 231.6, ◆ = 149.9, - = 21.9, ● = 9.6 (J m^{-3})

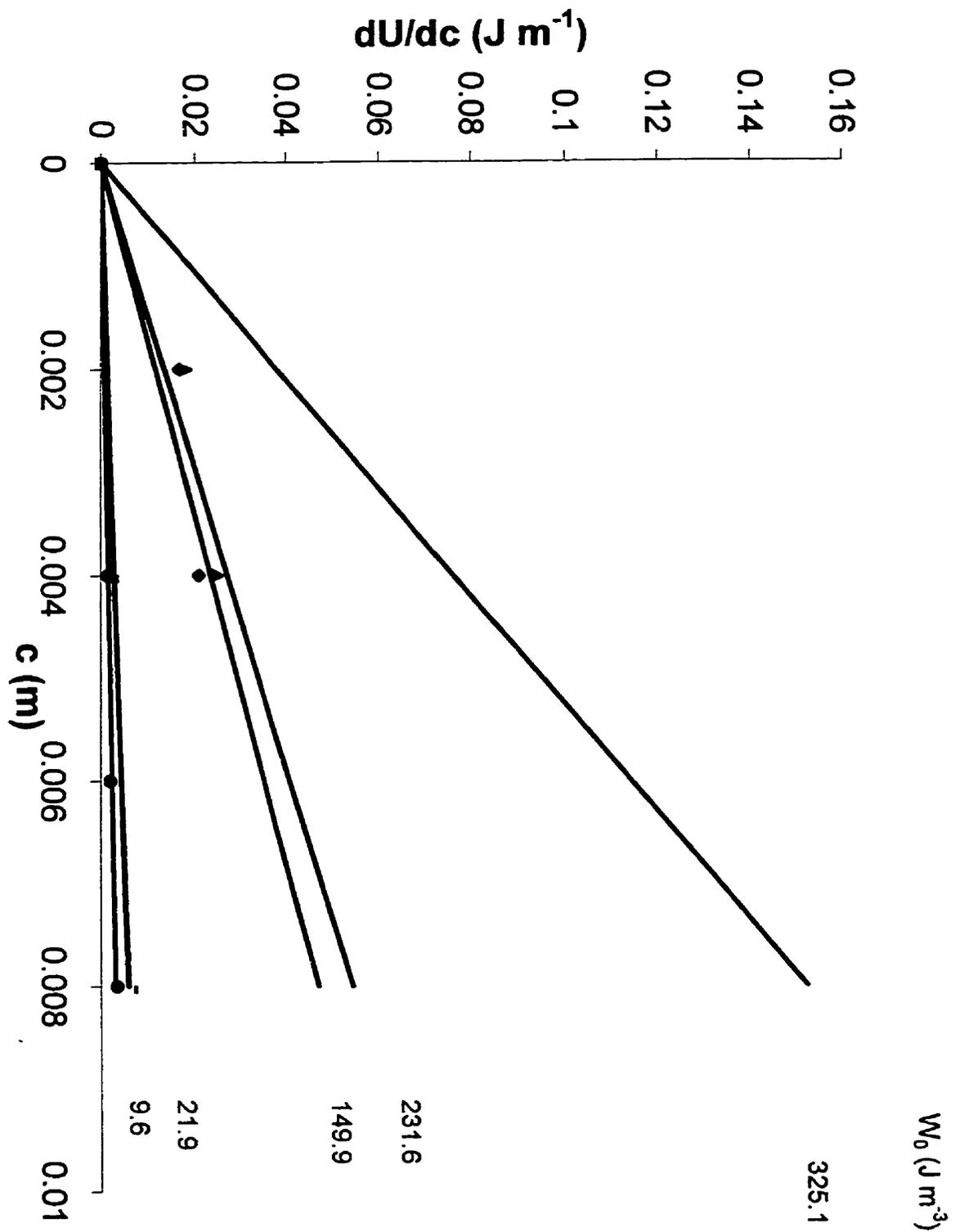


FIGURE 18. TOTAL INPUT ENERGY CHANGE PER UNIT OF CRACK EXTENSION AS A FUNCTION OF CRACK LENGTH (c) AT DIFFERENT ENERGY DENSITY LEVELS FOR 10 MINUTE FRIED POTATO CRUST ■ = 174.0, ▲ = 115.3, ● = 51.6, - = 36.2, • = 13.7 (J m^{-3})

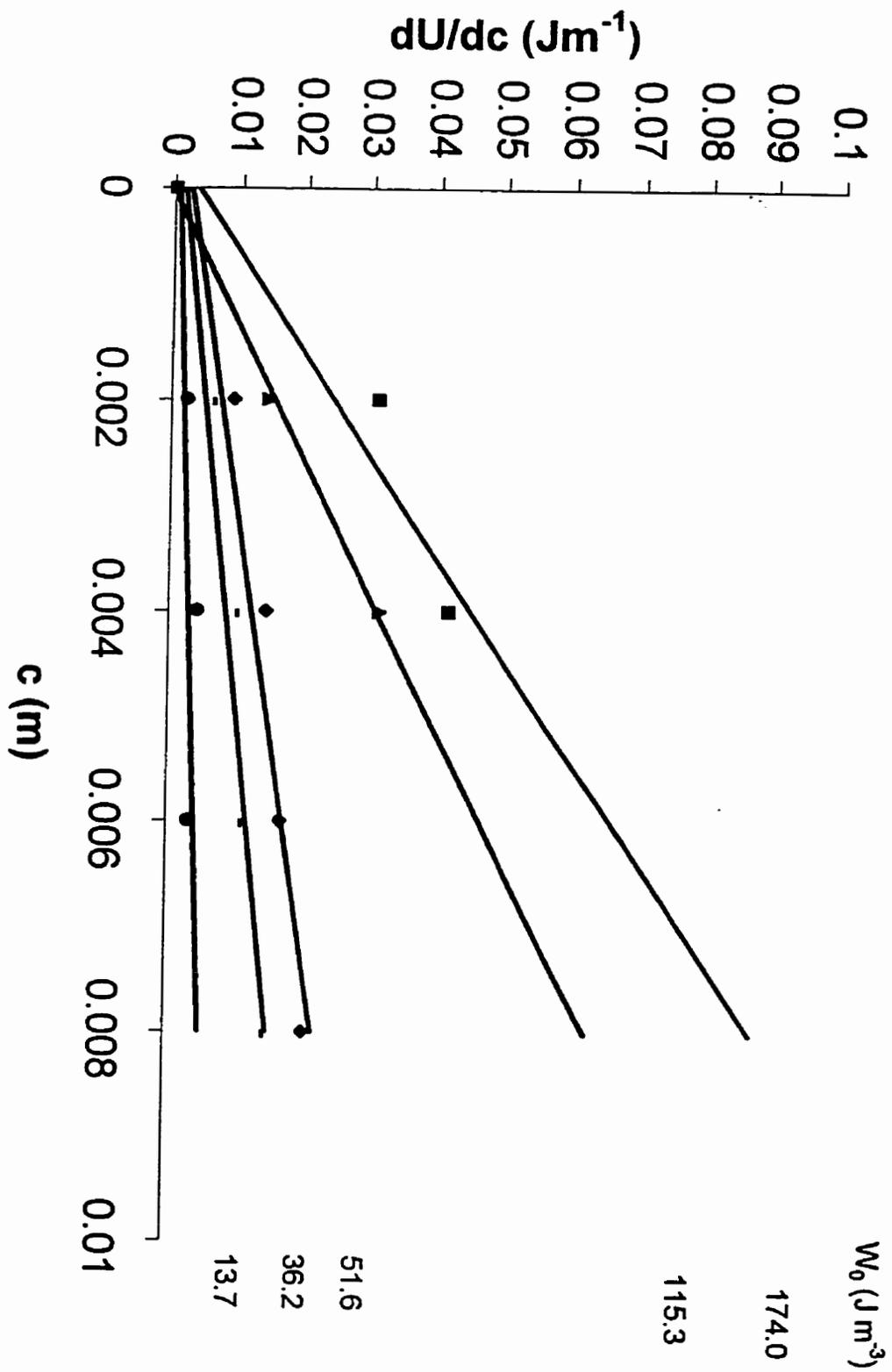


FIGURE 19. THE DEPENDENCE OF THE FUNCTION k_1 ON THE INPUT ENERGY DENSITY (W_0) FOR 1 MINUTE FRIED POTATO CRUST

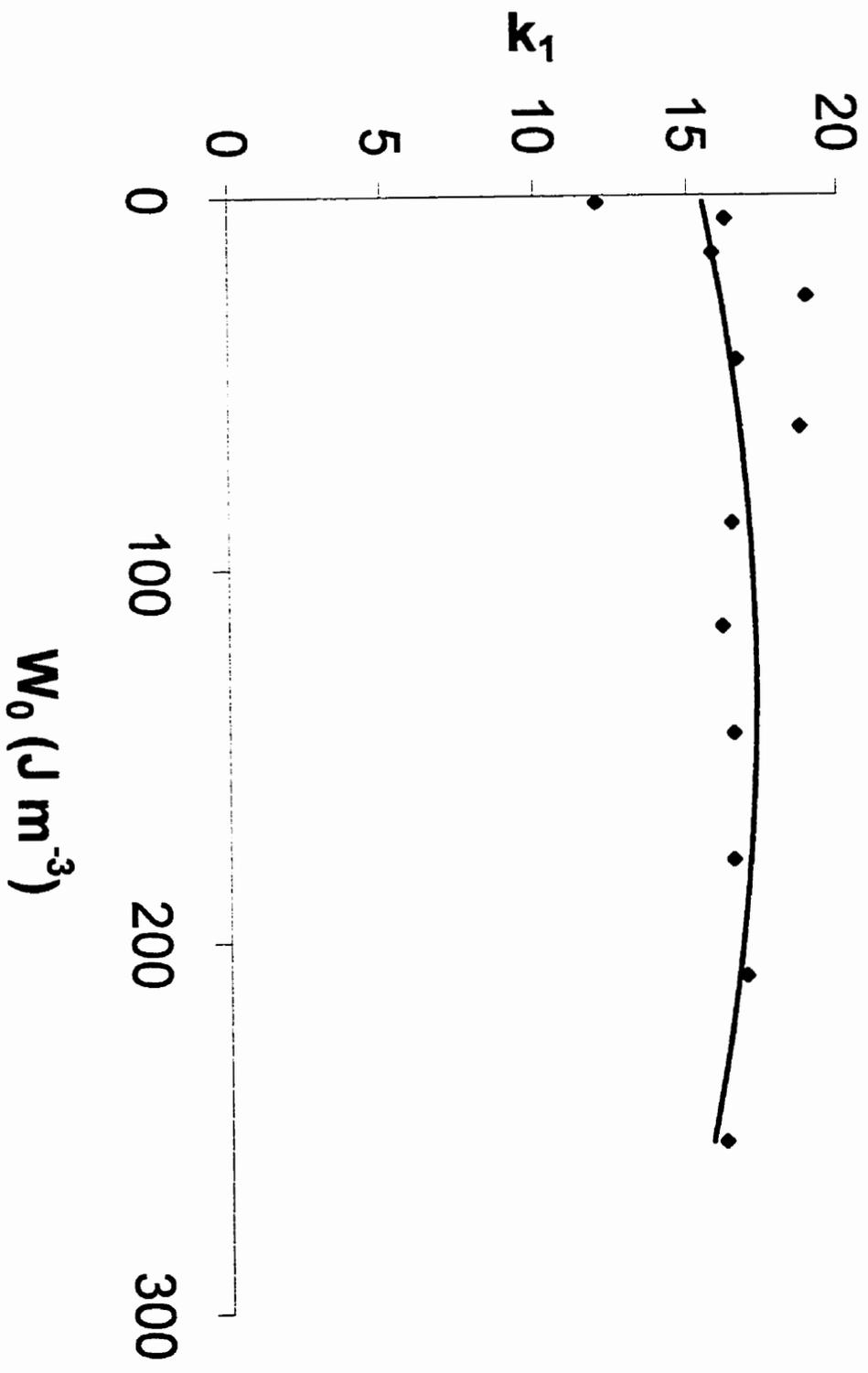


FIGURE 20. THE DEPENDENCE OF THE FUNCTION k_1 ON THE INPUT ENERGY DENSITY (W_0) FOR 2 MINUTE FRIED POTATO CRUST

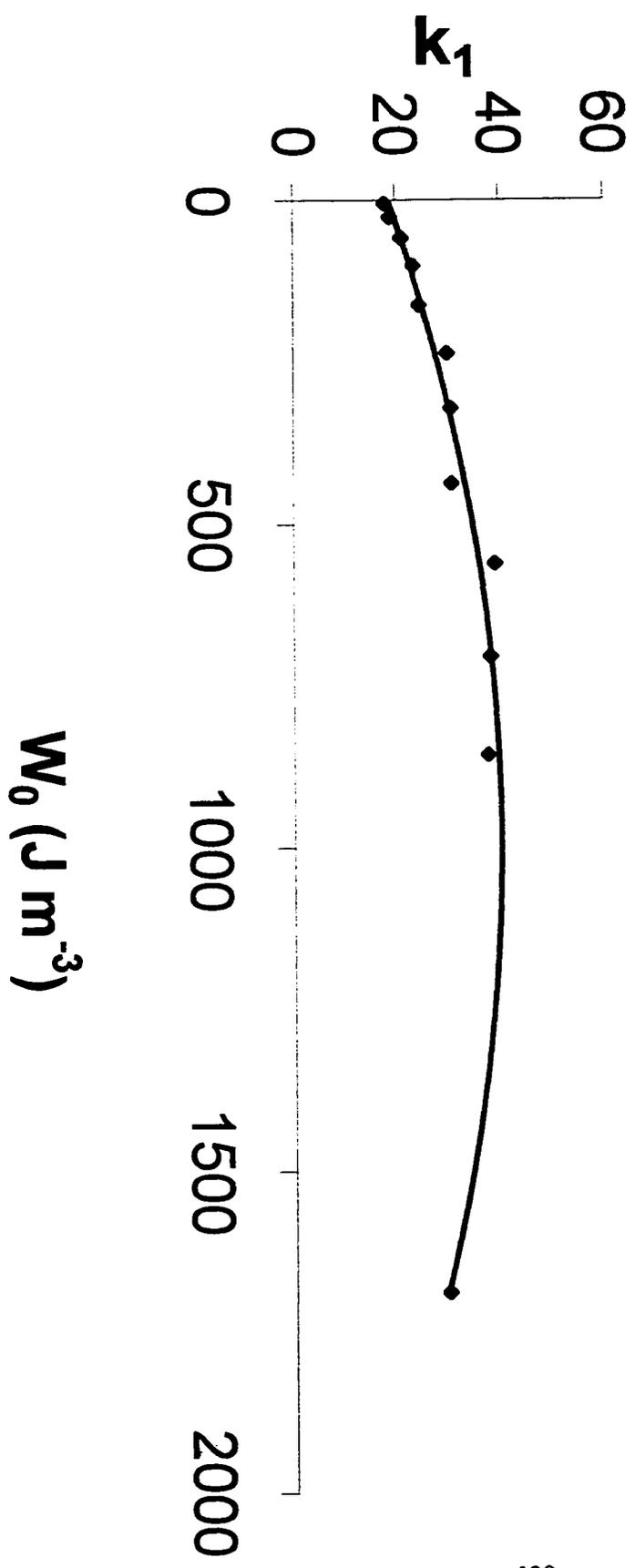


FIGURE 21. THE DEPENDENCE OF THE FUNCTION k_1 ON THE INPUT ENERGY DENSITY (W_0) FOR 4 MINUTE FRIED POTATO CRUST

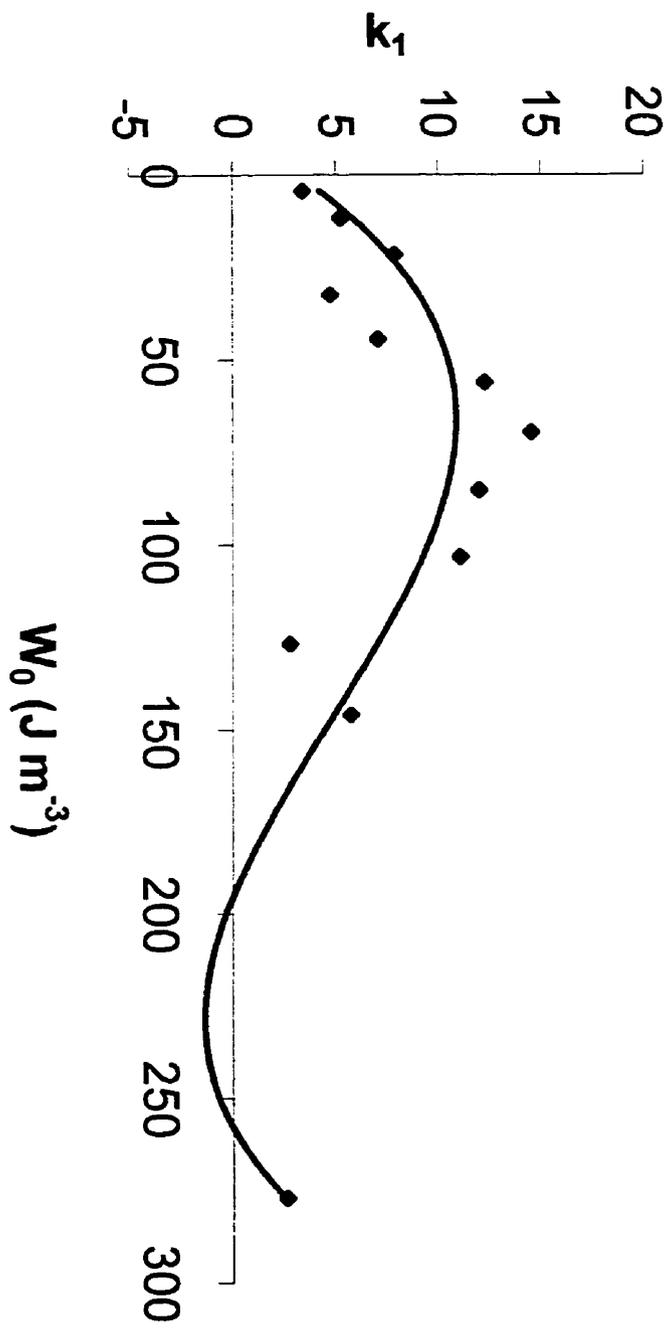


FIGURE 22. THE DEPENDENCE OF THE FUNCTION k_1 ON THE INPUT ENERGY DENSITY (W_0) FOR 7 MINUTE FRIED POTATO CRUST

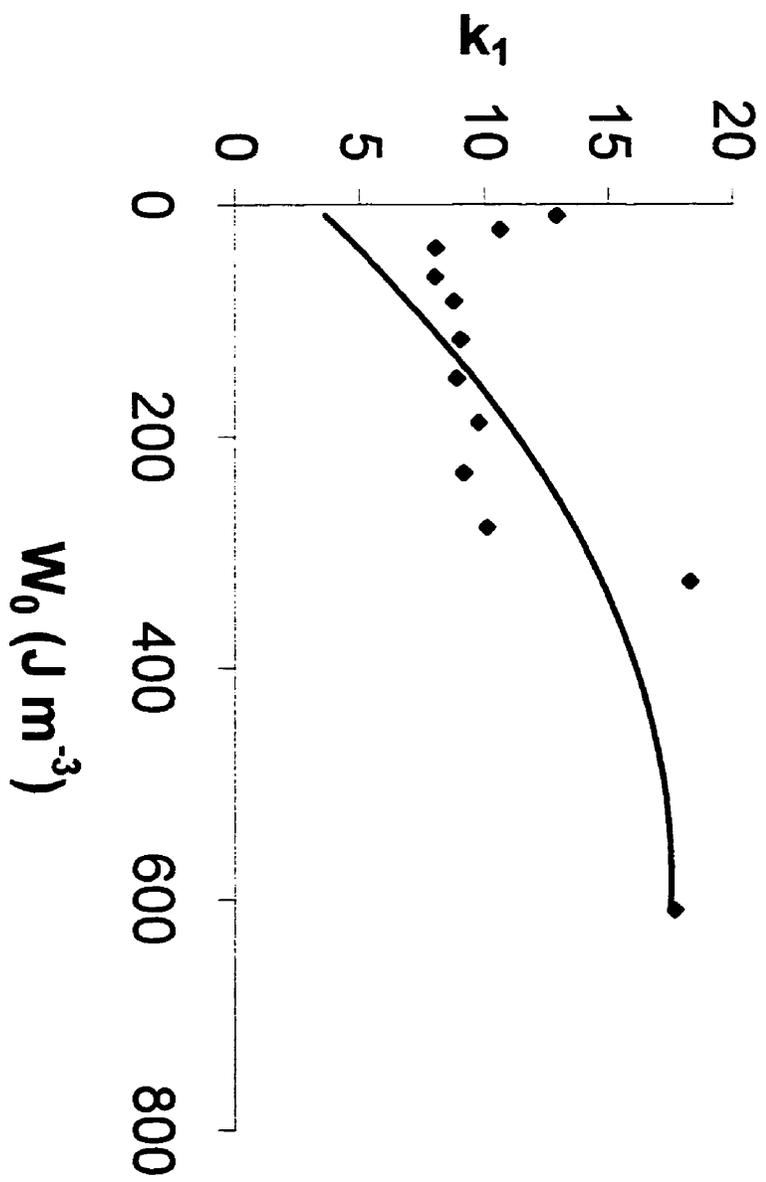
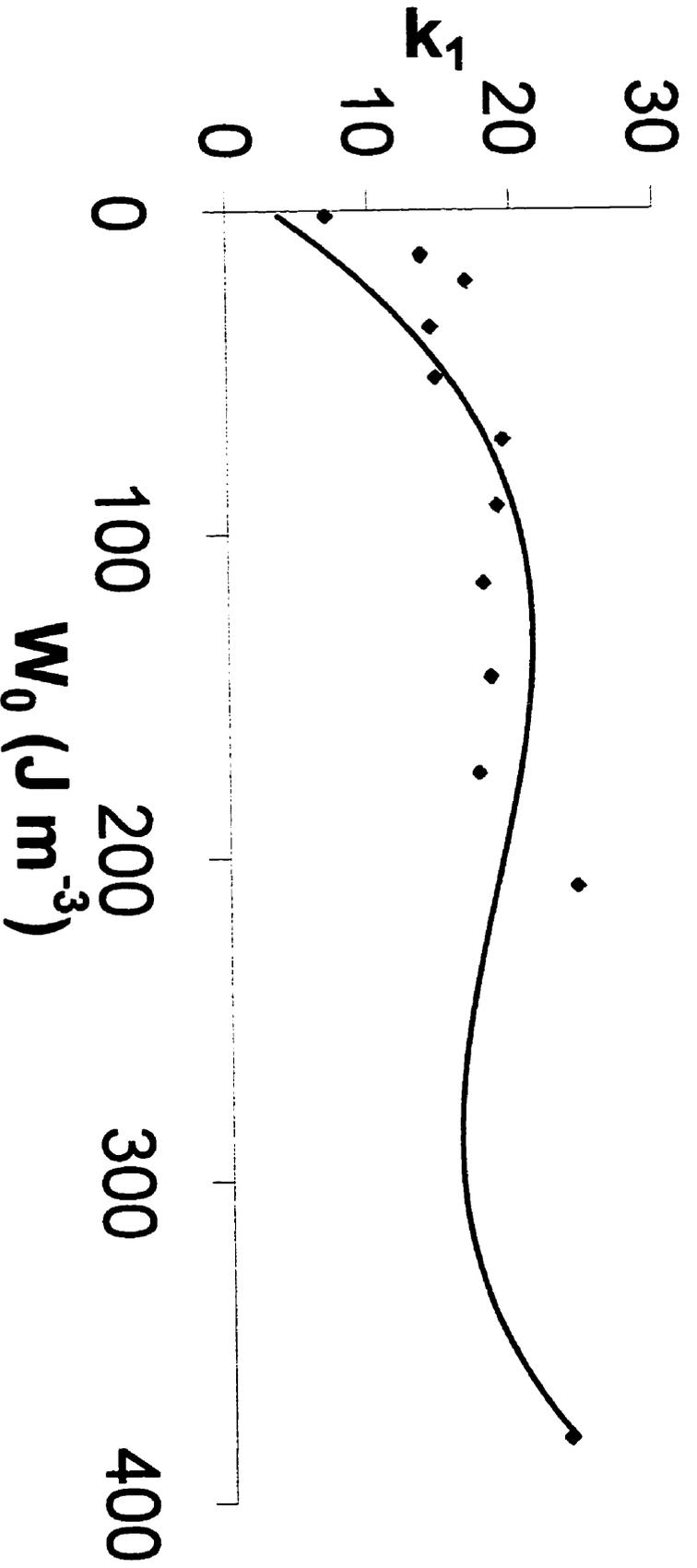


FIGURE 23. THE DEPENDENCE OF THE FUNCTION k_1 ON THE INPUT ENERGY DENSITY (W_0) FOR 10 MINUTE FRIED POTATO CRUST



4.4.2.3.2 Critical Energy Release Rate and Fracture Toughness

After determining $k_I(W_0)$, it was a simple matter to compute the critical energy release rate (T). At the point where crack propagation or fracture occurs, the input energy density, W_0 , will equal the critical input energy density, W_{0c} , for that specimen. For a perfectly elastic material, the critical apparent energy release rate, T , equals the fracture toughness (Andrews, 1974). The stress-strain curves, (Figures 8-12) for the crust of fried potatoes are quite linear, thereby indicating elasticity (Vincent, 1990). However, raw potatoes display markedly inelastic properties (Fahloul and Scanlon, 1996; Holt and Schoorl, 1983; Pang and Scanlon, 1996; Timbers *et al.*, 1966). The stress-strain curve for a raw potato specimen has been given by Fahloul and Scanlon (1996). By viewing this curve, it can be stated that it is notably more curved or non-linear than the stress-strain curve for fried potato crust. Equation 1 was rearranged to plot $k_I(W_{0c}) W_{0c}$ versus c^{-1} . A plot of $k_I(W_{0c}) W_{0c}$ against c^{-1} will give a straight line with a slope equal to the critical energy release rate providing T is constant and independent of c and W_0 (Andrews and Bhatti, 1982). This was performed for each of the fry times and is shown in Figures 24-28. The critical energy release rate for fried potato crusts was thought to be equal to the fracture toughness seeing that the stress-strain curves for fried potato crusts were remarkably linear and therefore little or none of the input energy was lost by hysteresis. The fracture toughness values of the fried potato crusts determined in this way are given in the second column of Table 5.

FIGURE 24. THE PLOT OF $k_1(W_{0c})W_{0c}$ VS THE RECIPROCAL OF CRACK LENGTH (c) FOR 1 MINUTE FRIED POTATO CRUST

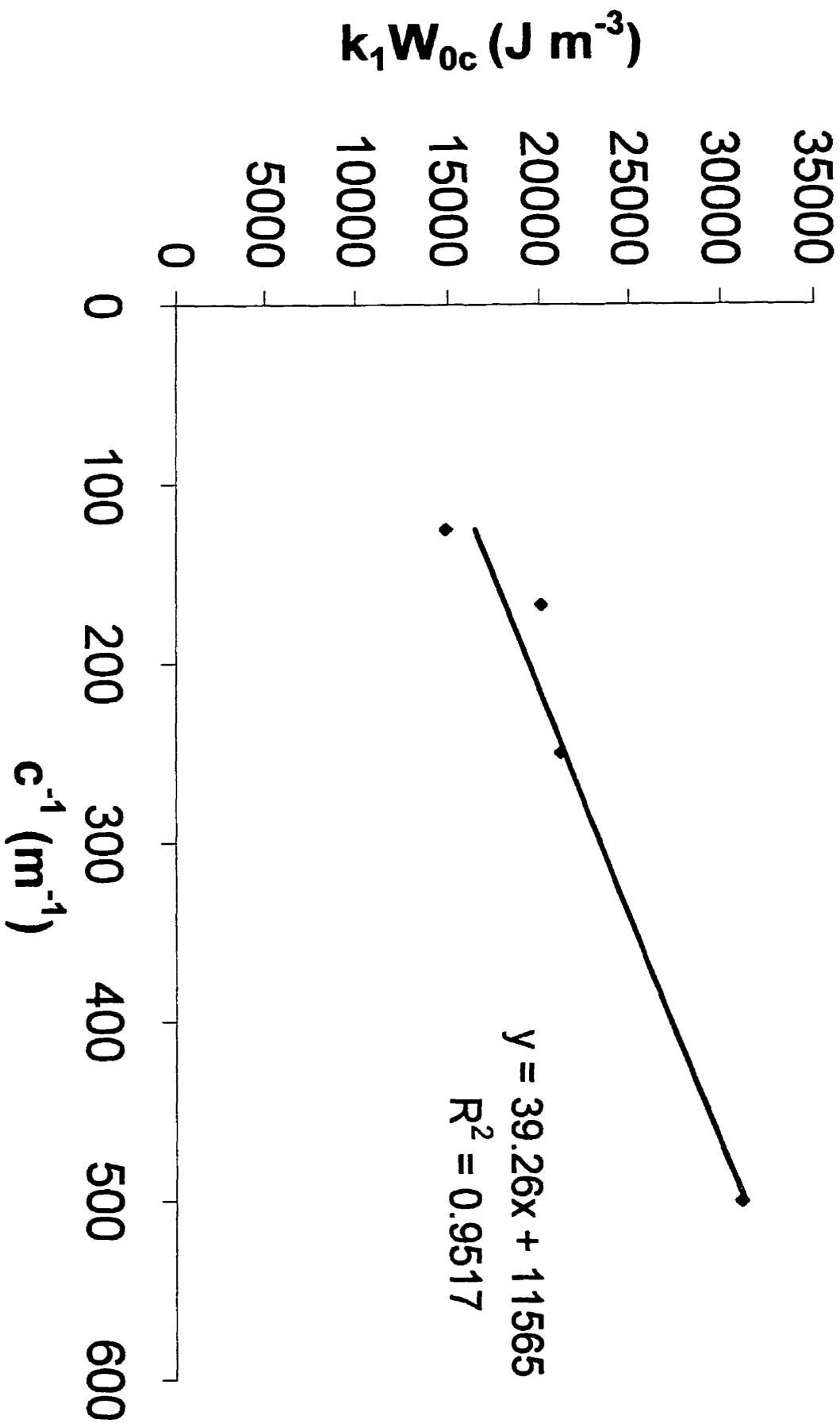


FIGURE 25. THE PLOT OF $k_1(W_{0c})W_{0c}$ VS THE RECIPROCAL OF CRACK LENGTH (c) FOR 2 MINUTE FRIED POTATO CRUST

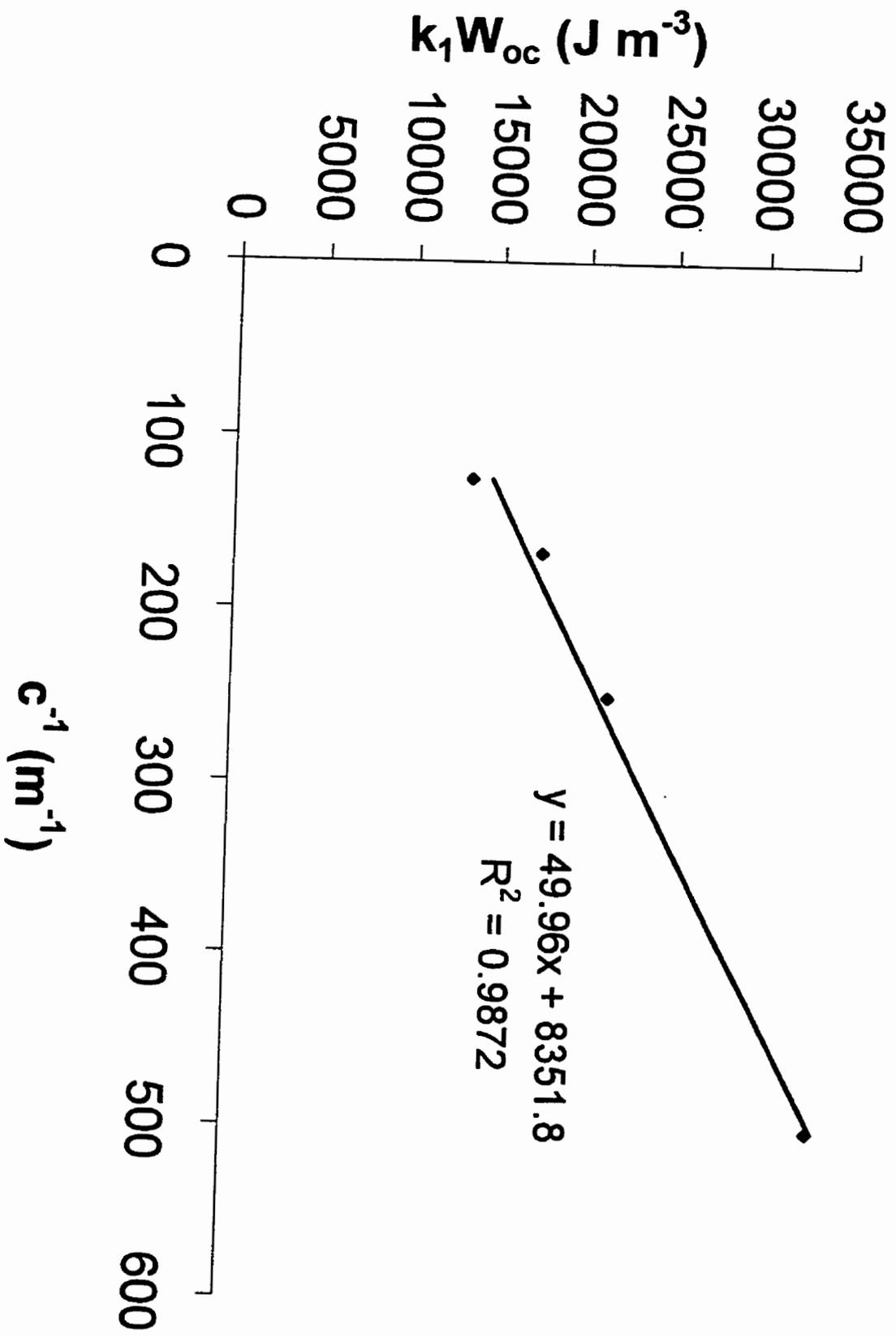


FIGURE 26. THE PLOT OF $k_1(W_{0c})W_{0c}$ VS THE RECIPROCAL OF CRACK LENGTH (c) FOR 4 MINUTE FRIED POTATO CRUST

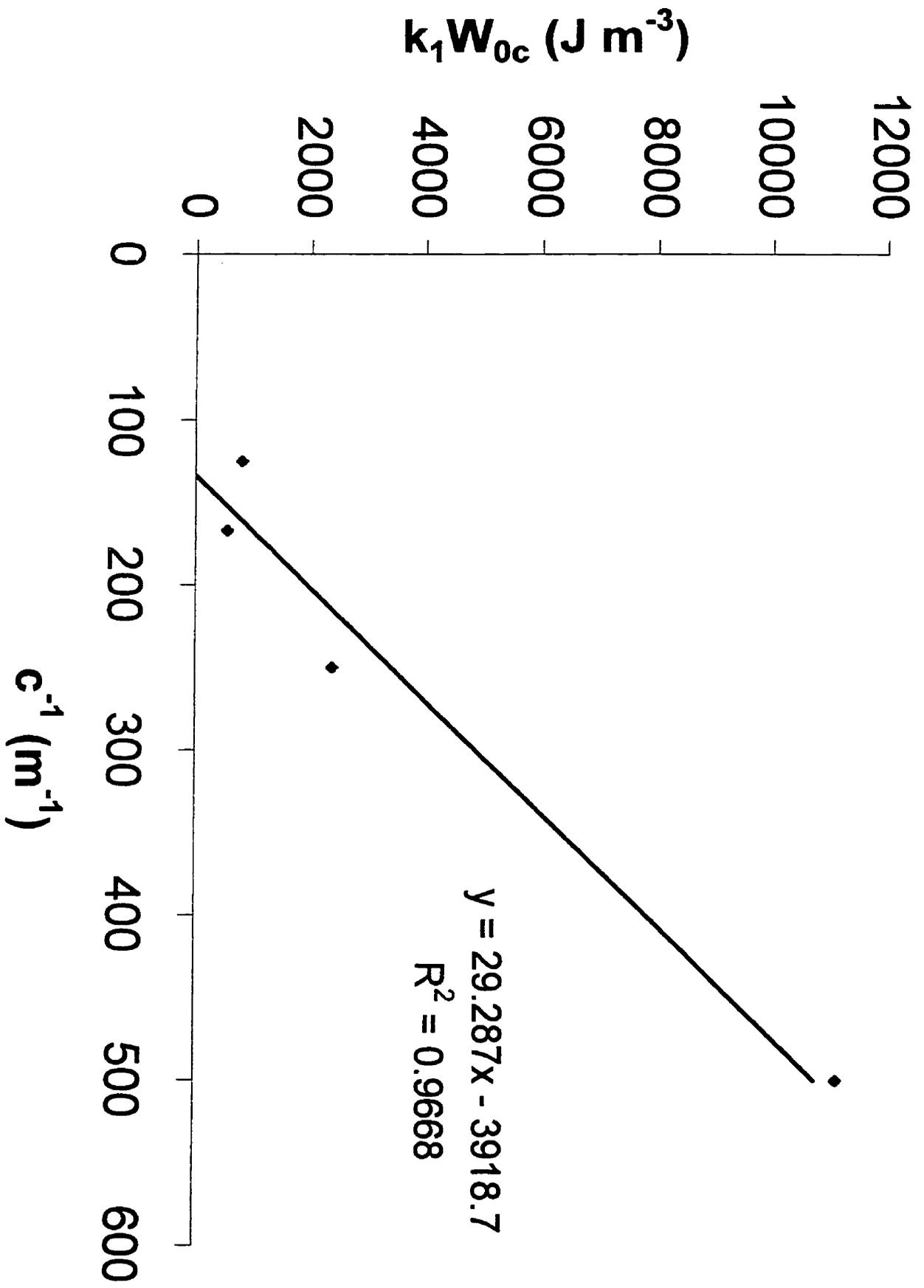


FIGURE 27. THE PLOT OF $k_1(W_{0c})W_{0c}$ VS THE RECIPROCAL OF CRACK LENGTH (c) FOR 7 MINUTE FRIED POTATO CRUST

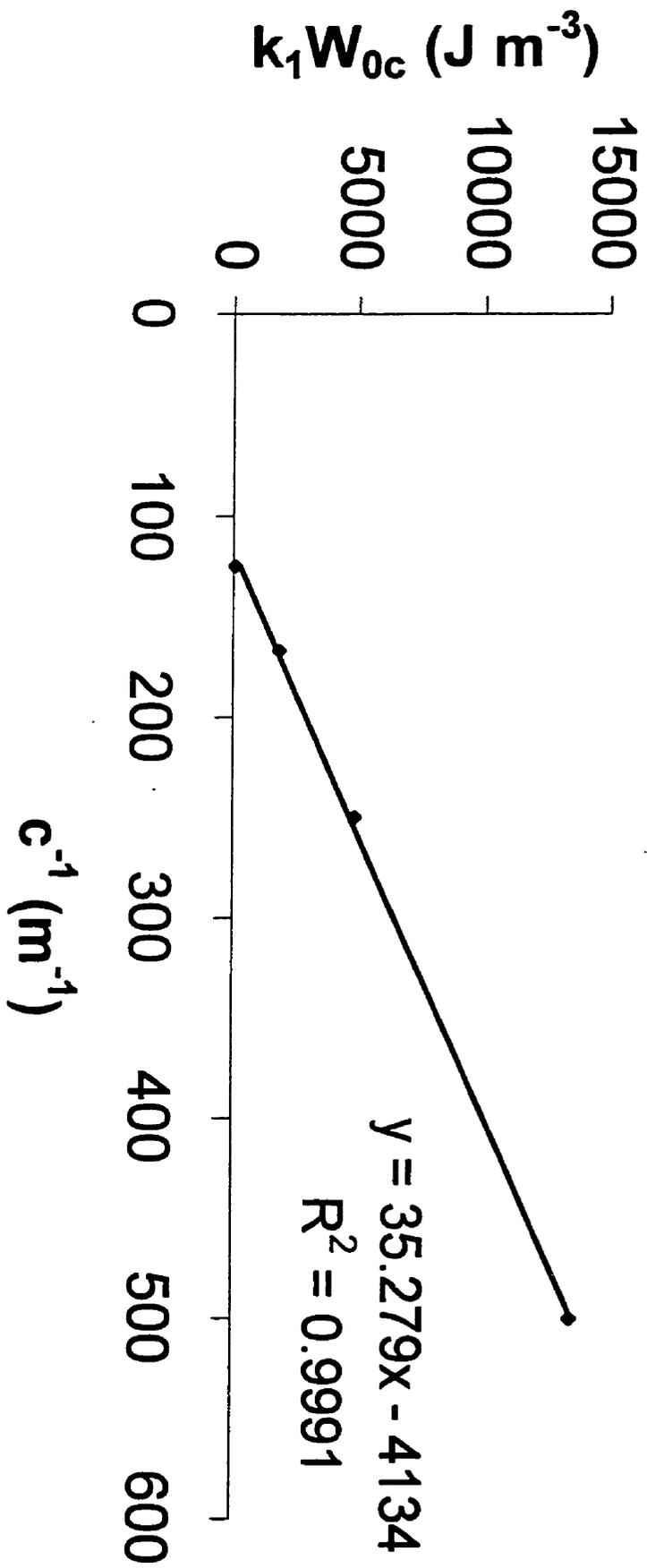


FIGURE 28. THE PLOT OF $k_1(W_{0c})W_{0c}$ VS THE RECIPROCAL OF CRACK LENGTH (c) FOR 10 MINUTE FRIED POTATO CRUST

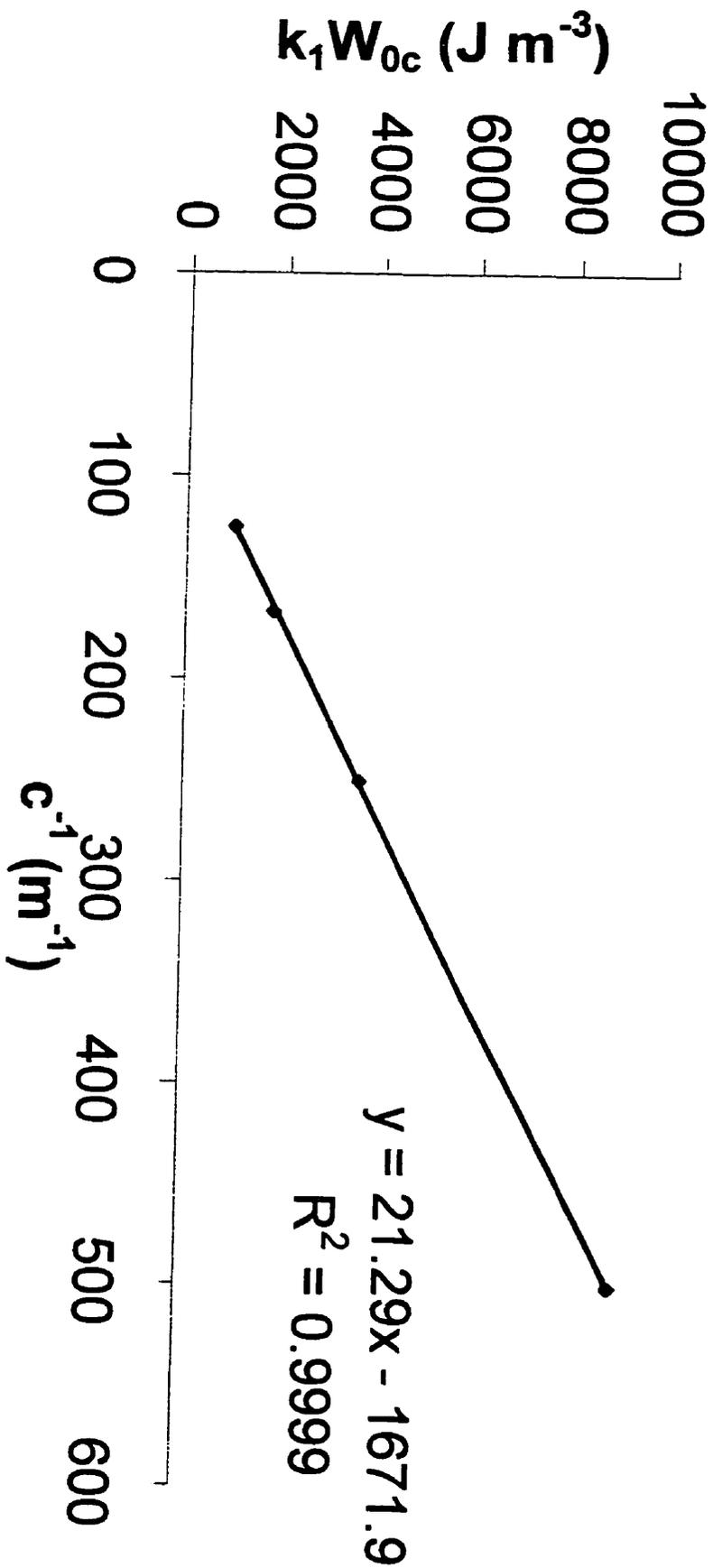


TABLE 5.**COMPARISON OF THE FRACTURE TOUGHNESS OF FRIED POTATO CRUST USING DIFFERENT METHODS OF EVALUATION**

Fry Time (minutes)	Fracture Toughness (J m ⁻²)	
	Generalized Fracture	Brittle Fracture
1 minute	39.26	1.47
2 minute	49.96	1.16
4 minute	29.29	1.06
7 minute	35.28	1.03
10 minute	21.29	0.68

4.4.2.4 Evaluation of Fracture Toughness Assuming Brittle Fracture

An alternative method of determining fracture toughness was investigated. This method was modeled after the work performed by Vincent (1982) in which brittle fracture was assumed. The fracture toughness for a brittle material is given by the following equation which assumes the state of strain at the crack being that of plane strain.

$$T = \frac{K_c^2(1-\nu^2)}{E} \quad (4)$$

Where: T is the fracture toughness, K_c is the stress intensity factor in the critical case, ν is Poisson's ratio, and E is the elastic modulus.

The stress intensity factor in the critical case can be related to the strength in the critical case (σ_c) of a material by:

$$\sigma_c^2 = K_c^2 \pi (1/cF_{cw}^2) \quad (5)$$

Where c is crack length and $F_{c/w}$ is a function that relates the crack length (c) present in a specimen to the width (w) of the specimen (Vincent, 1982). The determination of $F_{c/w}$ is given in the following equation (Vincent, 1982):

$$F_{c/w} = \frac{1.122 - 0.561(c/w) - 0.015(c/w)^2 + 0.091(c/w)^3}{[1-(c/w)]^{1/2}} \quad (6)$$

By plotting the square of the fracture stress or the strength in the critical case (σ_c^2) of a material against the reciprocal of crack length multiplied by the reciprocal of $F_{c/w}$ squared, a straight line is generated (Vincent, 1982). The slope of the line is $K_c^2\pi$ by which the stress intensity factor (K_c) can be readily calculated. This was done for the average fracture stress values of their corresponding crack lengths for all fry times. Figures 29-33 show these plots.

FIGURE 29. THE PLOT OF STRENGTH² VS 1/cF² FOR 1 MINUTE FRIED POTATO CRUST

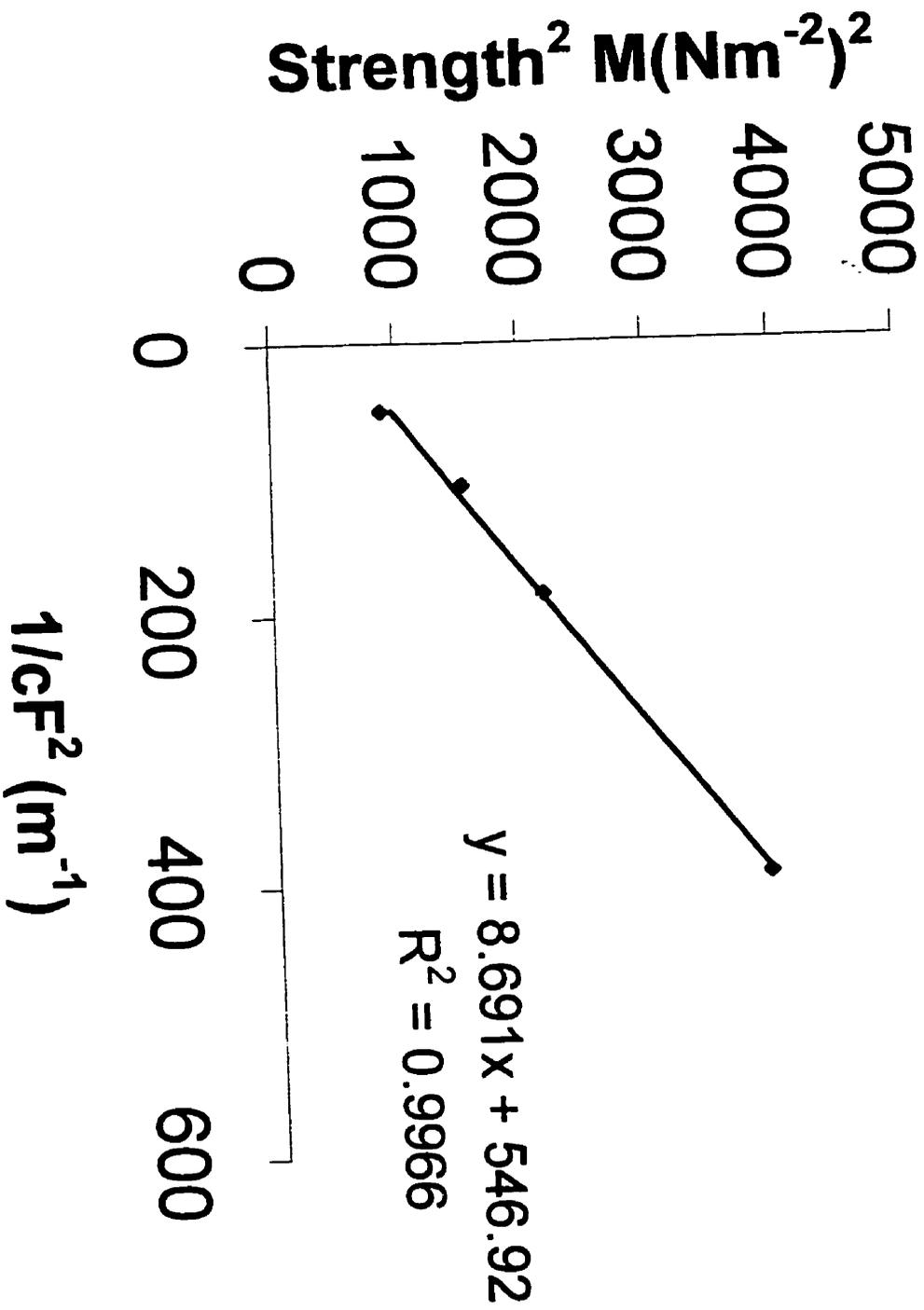


FIGURE 30. THE PLOT OF STRENGTH² VS 1/cF² FOR 2 MINUTE FRIED POTATO CRUST

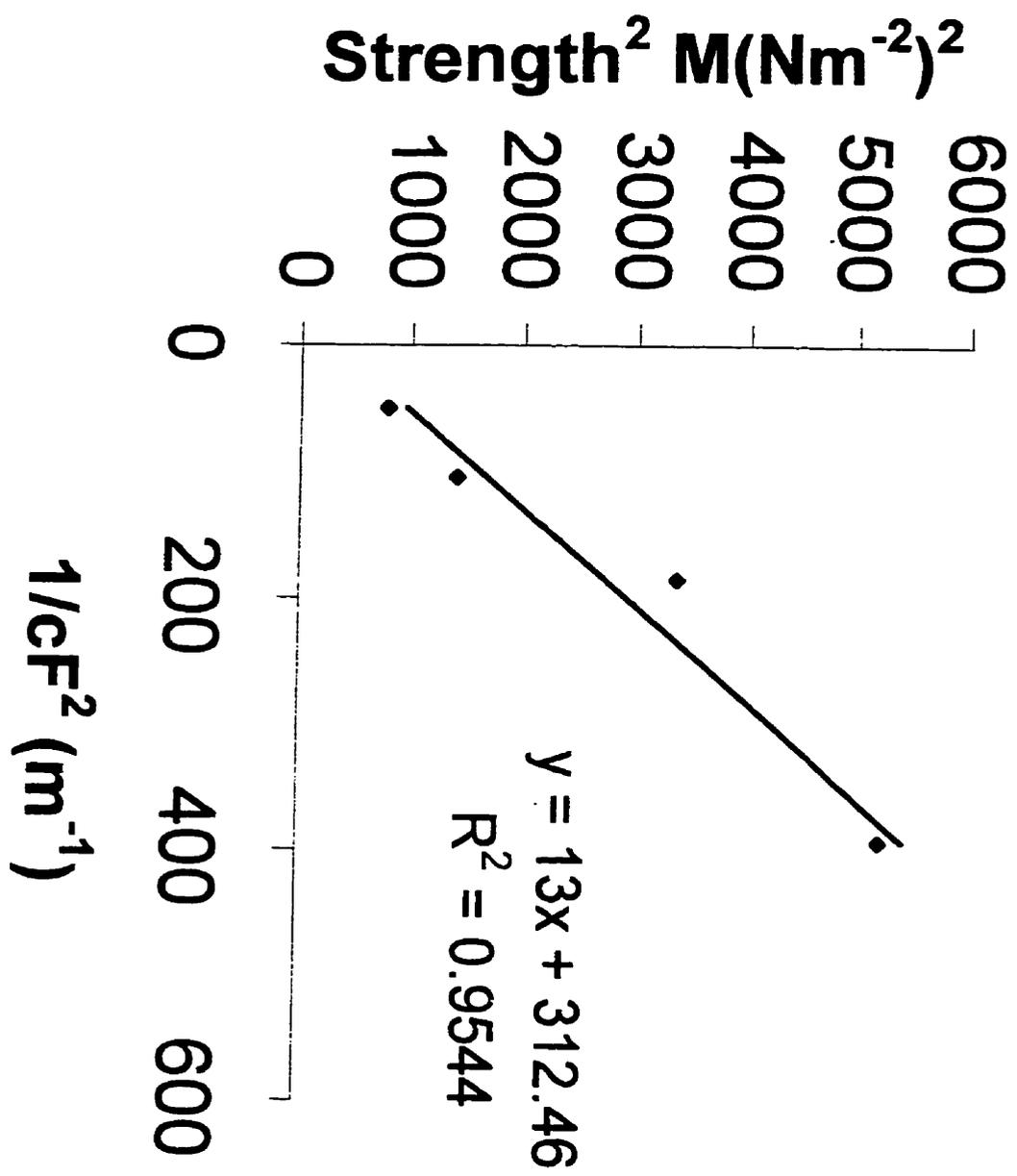


FIGURE 31. THE PLOT OF STRENGTH² VS 1/cF² FOR 4 MINUTE FRIED POTATO CRUST

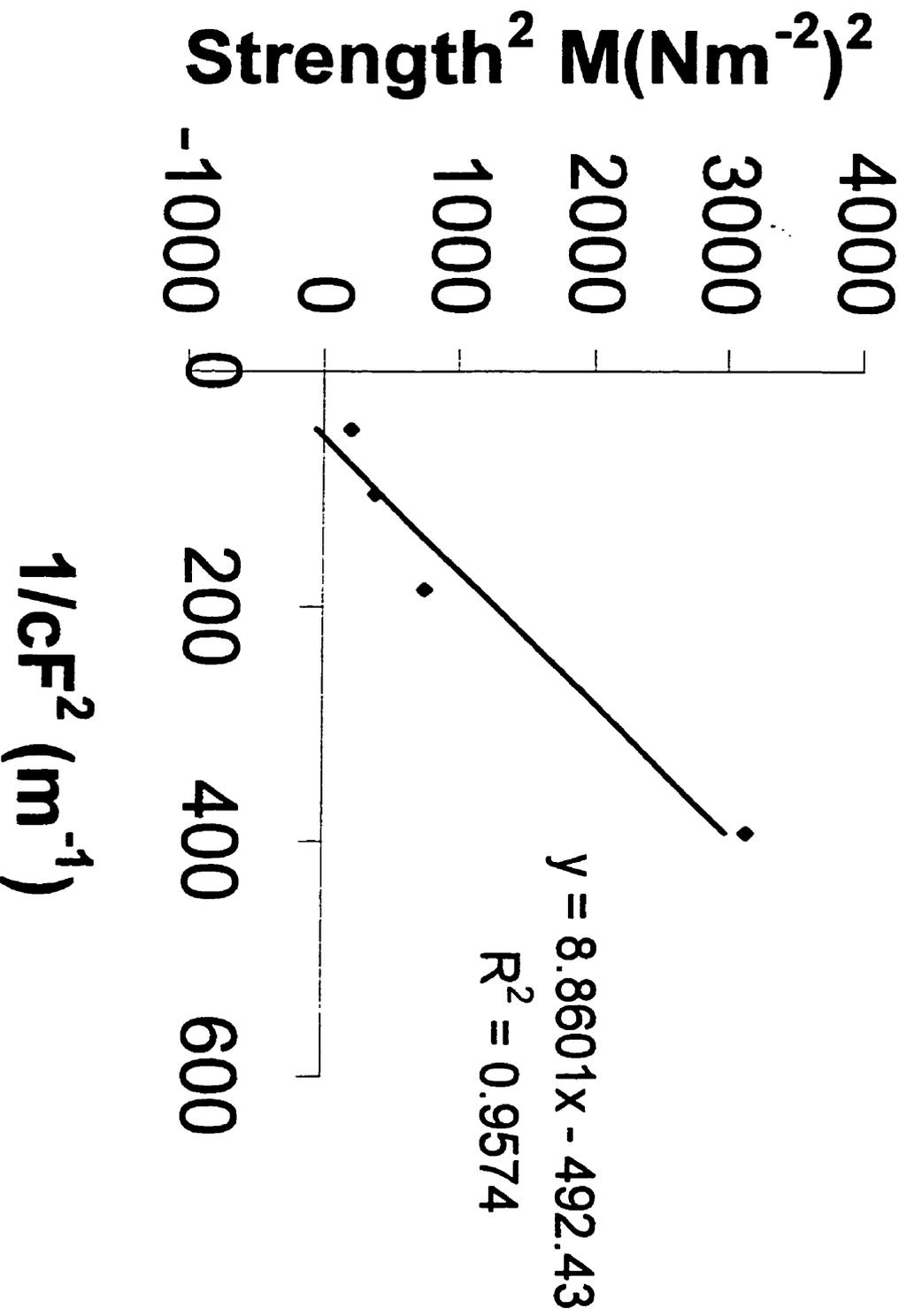


FIGURE 32. THE PLOT OF STRENGTH² VS 1/cF² FOR 7 MINUTE FRIED POTATO CRUST

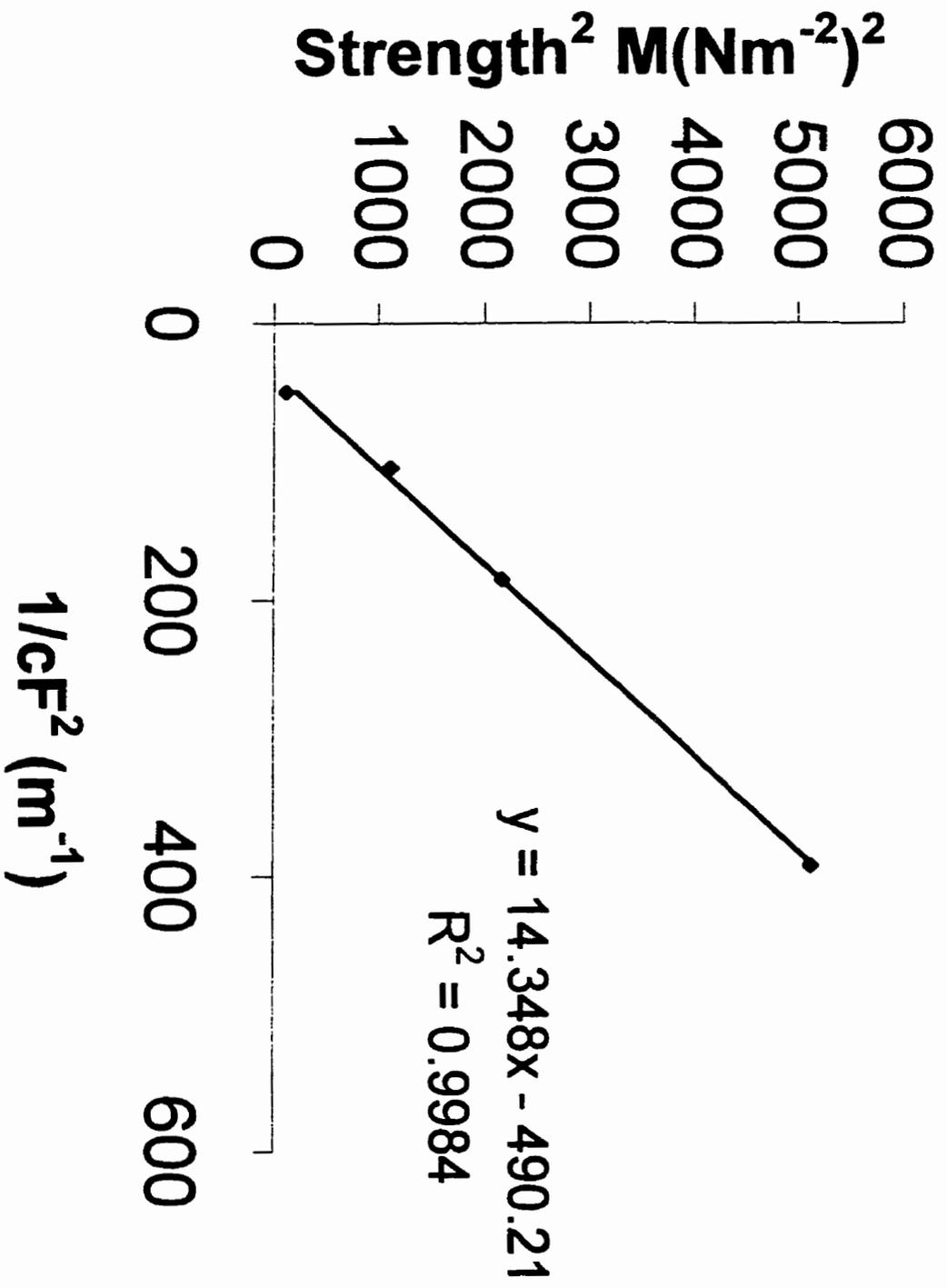
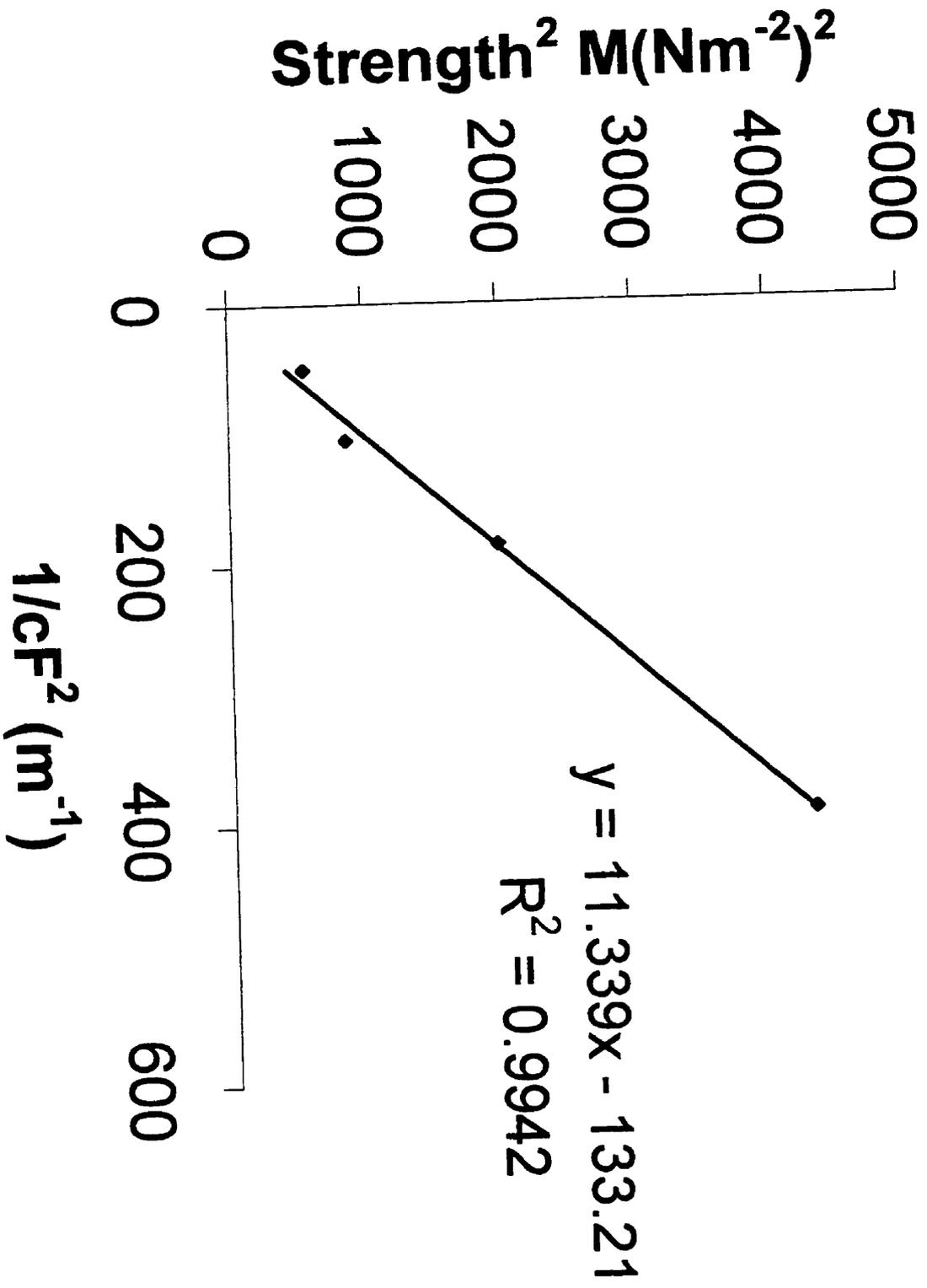


FIGURE 33. THE PLOT OF STRENGTH² VS 1/cF² FOR 10 MINUTE FRIED POTATO CRUST



Since the elastic moduli of the fried potato crusts were experimentally obtained and the Poisson's ratio of the fried potato crusts was qualitatively evaluated, the fracture toughness values of potato crusts fried for varying times could be obtained from Equation 4. These values are given in the third column of Table 5. The fracture toughness values for both methods show similar trends. As fry time increased, the fracture toughness values decreased. It has been noted that at longer frying times, more dehydration occurs (Saguy and Pinthus, 1995). Dobraszczyk (1994) stated that an increase in moisture content increases the energy required for fracture. Khan and Vincent (1993) attributed the higher fracture toughness values of potatoes compared to apples, in part, to the lower porosity exhibited by the potato. The high volume fraction of cell wall material and high adhesion of potato parenchyma requires higher forces to crack than apple and requires more energy to propagate a crack through it (Khan and Vincent, 1993). It has been stated that, in general, as frying time increases porosity of the food increases (Saguy and Pinthus, 1995). Thus, the potato crusts fried for a longer time would be more porous and have lower fracture toughness values. Interestingly, the brittle fracture approach yielded, on average, fracture toughness values 30 times lower than the generalized fracture mechanics approach. This may indicate that the fried potato crust was not completely brittle and that some plastic deformation remote from the crack surfaces had occurred. The previous assumption of perfect elasticity for the crust of a fried potato does not appear to be entirely valid. Since the fried potato crust may exhibit some inelastic nature, energy may be expended in initiating crack growth in addition to the fracture toughness (Wecharatana and Shah, 1983). The large difference between the fracture toughness values may be due in part to using an equation for brittle fracture (equation 4) that assumes the most severe case

of plane strain at the crack tip. Also, the difference between fracture toughness values obtained from the generalized fracture mechanics approach and the brittle fracture method may be in part due to an error in using a value of 0.5 for the Poisson's ratio. However considering the french fry crust may have had a Poisson's ratio with a value of 0 (the most extreme value compared to 0.5), the fracture toughness values from the brittle method would only increase by 33%. Therefore the Poisson's ratio can not be the only contributing factor to this difference in fracture toughness values

Work performed by Dobraszcyk (1994) indicates that there is a critical size of the specimen which defines a characteristic dimension at which a transition from brittle fracture to ductile fracture will occur. Below this size, the method of fracture is ductile. The critical specimen size at which a transition from brittle to ductile failure occurs is given by the following equation:

$$h_{crit} = \alpha ET / \sigma_c^2 \quad (7)$$

Where: h_{crit} is the critical specimen size (in terms of thickness) where the transition from brittle failure to ductile failure occurs, α is the test geometry factor assumed to be equal to one, E is the elastic modulus, T is the fracture toughness and σ_c is the fracture stress. Experimental values of E , σ_c , T (for both the generalized fracture mechanics approach and the brittle fracture approach) for all fry times were substituted into equation 7 and generally gave critical specimen sizes above (generalized fracture mechanics approach) or just below (brittle fracture approach) the thickness of the specimens used (See Section 4.3.2.1). The critical specimen size values for the generalized fracture mechanics approach for the 1, 2, 4, 7, and 10 minute fried potato crust specimens were

4.63, 12.48, 5.28, 13.19, and 4.1 mm, respectively. The critical specimen size values for the brittle fracture approach for the 1, 2, 4, 7, and 10 minute fried potato crust specimens were 0.22, 0.28, 0.35, 0.39, and 0.13 mm, respectively. Therefore plastic or ductile failure occurred and plastic energy was incorporated in the fracture toughness values of the generalized fracture mechanics approach.

Another explanation for the differences of fracture toughness values generated by the generalized fracture mechanics approach and the brittle approach may be purely mathematical. The choice of the polynomial function in evaluating k_I may be the reason for these differences. The polynomial fits may have overestimated k_I therefore giving greater fracture toughness values for the generalized fracture mechanics approach than the purely linear brittle fracture approach. Interestingly, by viewing Figures 31, 32 and 33 (longer fry times), it can be seen that the respective ordinate intercepts tend to approach 125, 141, and 117 m^{-1} , which are, within experimental error, the reciprocal of specimen width (10mm). This intercept is within reason. As crack length approaches the value of the specimen's width, the strain energy required to propagate a crack will tend to zero (Andrews and Billington, 1976). Simply stated, there is no fried potato crust remaining that will support the applied stresses that are imposed on the crust. This fact seems to indicate that the choices of the polynomial function in evaluating k_I were reasonable. Therefore the greater fracture toughness values for the generalized fracture mechanics approach compared to the purely linear brittle fracture approach were not due to mathematical conditions imposed on the generalized fracture mechanics approach but rather indicates true differences between the generalized fracture mechanics approach and the brittle fracture approach via the inclusion or exclusion of plastic deformations remote from the crack

4.5 CONCLUSIONS

From a point of view of incorporating control of texture within a unit process operations approach to food processing, it is desirable if the mechanical properties of raw or manufactured food products are used to characterize the textural characteristics of these foods. Mechanical parameters are fundamental material properties, which are independent of the geometry of a material (i.e. size and shape) and are widely used for materials specifications. Their values are expressed in SI units, despite the variability in the mechanical properties of biological materials. Mechanical properties are an objective fundamental measure of textural quality and many researchers have acknowledged the benefits of obtaining fundamental measures of food texture. This section has shown that the mechanical properties of fried potato crust can be measured with a commonly used structural materials test namely, the tensile test. The tensile test was used to measure the fracture stress, fracture strain, elastic modulus, and fracture toughness of fried potato crust. It was observed that there is a relationship between length of frying time and the mechanical properties of the fried potato crust. As duration of frying time increased, the values of elastic modulus and fracture toughness increased while the values of fracture strain decreased. Also, two different approaches for calculating fracture toughness values were investigated: generalized fracture mechanics approach and brittle fracture approach. The generalized fracture mechanics approach yielded fracture toughness values nearly 30 times larger than the brittle fracture approach. The Poisson's ratio of the fried potato crust was unable to be measured quantitatively, yet microscopy was performed to qualitatively obtain a value for Poisson's ratio. This indicates that the mechanical properties of biological materials can be obtained. However, further study of the measurement of

mechanical properties is necessary to effectively used mechanical properties as indices of textural properties. With respect to potatoes and processed potato products, fracture stress, fracture strain, elastic modulus, Poisson's ratio and fracture toughness measurements could serve to quantify textural changes that are technologically important to the potato processing industry.

5.0 PAPER 3

**A FUNDAMENTAL MECHANICAL ANALYSIS OF THE INDENTATION
PROCESS OF A BIOLOGICAL COMPOSITE MATERIAL CONSISTING OF
FRIED POTATO CRUST AND AN AGAR GEL**

5.1 ABSTRACT

A full mechanics approach was applied in the indentation analysis of a biological composite material. A 3% agar gel was modeled as the core of the composite material and fried potato crusts with various thicknesses were modeled as the facesheets of the composite material to simulate the structure of a french fry with the aim of characterizing the indentation process. Using a theory, which incorporated small plate deformation theory and plastic deformation theory, and membrane deformation theory, the load-deformation response of this biological composite material was characterized. The theoretical predictions were in reasonable agreement with the experimental results. At indentation deformations less than half the crust thickness, the indentation process was characterized by the linear-small plate deformation theory. At indentation deformations greater than half the crust thickness but less than the total crust thickness the indentation process was characterized by non-linear plastic deformation theory. At indentation deformations greater than the total crust thickness, the indentation process was defined by the membrane theory.

5.2 INTRODUCTION

Large numbers of potatoes are being used for processing purposes and the quality of raw and finished potato products has become very important (Manitoba Agriculture, 1998). Talburt *et al.* (1987a) stated that texture is a major factor in determining the quality of whole cooked potatoes and processed potato products. There is no standard method used for measuring the textural characteristics of french fries (Ross and Porter, 1969). The textural properties of french fries are not easily determined because of their structure. A french fry consists of two components, the crust, which is a crisp exterior; and the core, which is a soft mealy interior (Voisey *et al.*, 1974). It is these two components, namely the crust and the core, that characterize the texture of a french fry. It follows that french fries can be considered to be a type of composite material since french fries consist of two principal components that differ in their textural properties and thus their mechanical properties. Recently, there has been increased interest in the mechanical properties of advanced composite materials that are used in the aerospace industry (Sakamoto *et al.*, 1991). This interest has led to an increase in the study and research of anisotropic elasticity encountered in composite materials such as sandwich panels

Static indentation analysis of composite sandwich panels has been studied analytically and experimentally (Olsson and McManus, 1996; Frostig *et al.*, 1992). Olsson and McManus (1996) used a theory that likened the indentation process to impact loading. Their theory was also based on the assumption that the load being applied was concentrated on an elastic infinite face-sheet that rested on a core that was bonded to a rigid foundation. After core yielding, the contact problem was considered to have separate

regions: there was an outer region and an inner region. The outer region was modeled as a plate on an elastic foundation. The inner region was modeled using small plate deformation theory, large plate deformation theory, and membrane theory. By using this type of analysis, Olsson and McManus (1996) found that the load history for the indentation of a composite material consisted of three regimes: linear elastic, non-linear plastic, and non-linear plastic with membrane stresses. Therefore, acknowledging all three of these regimes in the indentation analysis of a composite material, a more accurate theoretical model describing the indentation process is possible.

By viewing indentation testing with respect to obtaining texture measurements, the food industry often employs indentation testing as an expedient method of texture evaluation (deMan, 1969). It follows that the test methods developed in the discipline of mechanical engineering for industrial composite materials can be very helpful in the analysis of biological composite materials (Sakamoto *et al.*, 1991). It was postulated that a full mechanics analysis could be used to describe the indentation process of a biological composite material consisting of fried potato crust and an agar gel. Therefore, with more study, a fundamental evaluation of french fry texture would be feasible from performing simple indentation tests. Admittedly, potatoes are highly variable in structure and mechanical properties (Fahloul and Scanlon, 1996; Pang and Scanlon, 1996; Voisey *et al.*, 1969). In order to simplify the mechanical analysis, an agar gel was used as a model system for the french fry core. Agblor (1997) reported peak force values of french fry core material obtained from indentation tests. These values were comparable to the indentation derived peak force values for a gellan gel (mechanical properties of the same magnitude as an agar gel, Nussinovitch *et al.*, 1990). The use of a gel permitted the removal of a highly

variable layer in the composite material and thus allowed for improved accuracy of the analysis. The objective was to perform a mechanical analysis on a french fry crust-agar composite, thereby validating, that a true french fry composite could be analyzed.

5.3 METHODS AND MATERIALS

5.3.1 Potatoes

Potatoes of the cultivar Russet Burbank were used as the experimental material, obtained from a commercial processing crop grown on a site near Carberry, Manitoba. Potatoes delivered from commercial storage in January 1997 were stored at the Horticultural Storage Research facility at the University of Manitoba. The potatoes were held at $8 \pm 1^{\circ}\text{C}$ and at a minimum relative humidity of 90% until used for processing. Potatoes obtained in January 1997 were used for the experimental work

5.3.2 Potato Processing

For the experimental work, the potatoes were processed in order to obtain enough specimens for each fry time chosen. Approximately five usable slices were obtained from each tuber. For the main experimental work potatoes were processed in order to process enough specimens for each fry time chosen. The potato slices were randomly split into 5 groups and were processed with five fry times: 1, 2, 4, 7, and 10 minutes.

For the experimental work, all tubers were removed from storage and peeled just prior to processing. Slices (slabs) of 10 mm thickness were sliced lengthwise off potatoes from the stem end to the bud end. These potato slabs were processed according to the

procedure followed in the commercial potato processing industry as described by Agblor (1997). Immediately after blanching and drying (Agblor, 1997) the potato slabs were placed in a wire frying basket and fried for various lengths of time in a thermostat controlled deep fat fryer (Garland Model 80-03, Mississauga, ON) set at 185 ± 2 C. The frying oil was hydrogenated canola oil with the trade name of Crisco Professional Frying Oil (Procter and Gamble, Toronto, ON). The amount of potato slabs (approximately 200) fried for the experimental work was obtained without needing to change the frying oil. After frying, adhering oil was removed by agitating the wire basket. The fried potato slabs were placed on a metal tray in a single layer and frozen. For freezing, the trays were placed in a walk-in air freezer (Model WTD, Coldstream Refrigerator Mfg. Ltd, Winnipeg, MB) at -20 C. They were placed close to a fan to simulate conditions in a blast freezer (Agblor, 1997). The fried potato slabs were frozen overnight on trays and then transferred to pre-labeled ziploc freezer bags and stored at -20 C until needed.

5.3.3 Specimen Preparation

The crusts of the potato slabs were removed by slicing the frozen potato slabs with a Hobart slicer (Model 410, Hobart Manufacturing Co., Cincinnati, OH). Each batch of potato slabs fried for a certain time had a different average crust thickness. Preliminary experimentation determined how to calibrate the slicer for each fry time (by trial and error) in order to obtain crust slices with a minimum amount of inner core attached to the crust. When the correct setting was determined for each fry time, it was marked on the slicer and used for obtaining subsequent crust slices. After the crust slices were obtained, they were placed on paper towels and put in ziploc plastic bags to prevent moisture loss.

The dimensions of the specimens obtained from the crust slices were cut to a length of 40 mm and a width of 40 mm with a sharp blade. The thickness of the specimens was dependent upon fry time. The average thickness of the specimens with 1, 2, 4, 7, and 10 minute fry times were 0.63, 0.96, 1.29, 1.60, and 1.86 mm, respectively. For each fry time, 25 specimens were used to generate the values of average thickness. One crust specimen was glued to each agar cube tested. Each specimen was glued to an agar cube with 40 mm X 40 mm X 40 mm dimensions with cyanoacrylate adhesive (Viachem, St. Laurent, PQ). A thin layer of glue was spread onto one face of an agar cube, the crust was placed on, and the 'french fry' composite was let to set for one minute. In order to quantify the layer of the glue, an auxiliary experiment was performed. Glue was spread onto an agar cube and allowed to set/dry. The layer of glue was sheared off with a sharp blade. The thickness of the layer of glue was quantified with two methods. 1) The layer of glue was held with tweezers and measured under a micrometer calibrated Nikon Optiphot compound light microscope (Chiyoda-Ku, Tokyo, Japan). 2) The layer of glue was held with two pairs of tweezers and indented into a petroleum jelly coated microscope slide. The average thickness of the layer of glue was quantified by measuring the thickness of the indentation on the petroleum jelly coated slide using a Nikon Optiphot compound light microscope (Chiyoda-Ku, Tokyo, Japan) calibrated with a micrometer. The value of the thickness of the glue layer obtained was an average of these two techniques since there was no substantial difference in values obtained by the two methods.

5.3.4 Agar Gel Preparation

A 3% agar gel (3g/100ml) was prepared by dissolving microbiological grade granulated agar (Difco, Detroit, MI) in distilled water. The solution was heated until boiling in an Erlenmeyer flask on a hot plate. The liquid agar dispersion was poured into a pan and cooled overnight at room temperature prior to attachment of the fried potato crust specimens and subsequent testing 24 hours later. The composite fried potato crust-agar system was tested immediately after the fried potato crust was glued to the agar cube.

5.3.5 Indentation Testing

The indentation testing was performed at room temperature under quasistatic conditions. The Lloyd L1000 universal testing machine (Lloyd Instruments Ltd, Fareham, England) was used for the application of a normal force with a crosshead speed of 1 mm·min⁻¹.

The indenters employed for indentation testing were flat ended cylinders with 0.5, 1.0, 2.0, 3.0, and 4.0 mm diameters. Since agar cubes of 40mm X 40mm X 40mm dimensions were indented with these indenters, the composite fried potato crust-agar specimens could be modeled as an elastic half-space (i.e. the agar-crust composite had dimensions much larger than the dimensions of the indenters used).

Testing took place over six days with two indenters being used for indentation testing on each of the first five days. On the sixth day all five indenters were used. For each of the first five days of testing, agar from two different pans were used to create the composites; ten cubes of agar of the desired dimensions were obtained from each pan. For the sixth day of testing, agar from three different pans were used for testing; a total of 25

cubes being used to create the composites. The pairing of the indenters for testing were as follows: Day 1) 1 and 4 mm diameter indenters, Day 2) 3 and 0.5 mm diameter indenters, Day 3) 0.5 and 2 mm diameter indenters, Day 4) 2 and 3 mm diameter indenters, and Day 5) 4 and 1 mm diameter indenters. Testing of ten composites was performed with the first indenter followed by testing of ten composites with the second. On the sixth day all five indenters were used in random order.

On each day of testing the crusts resulting from different fry times were glued to randomly chosen agar cubes. Composites of the crust from each fry time were tested twice for each of the probes for each of the first five days, and once for the sixth day. Thus, a total of five replicates were tested for each fry time and each indenter diameter for a total of 125 load-deformation curves.

5.4 RESULTS AND DISCUSSION

5.4.1 Linear Elastic Regime

Indentation to a deformation level that is equal to half of the thickness of the crust has been modeled with the small plate deflection solution so that the 'french fry' composite has elastic properties and can be considered to be in the linear elastic regime (Roark, 1954). This linear elastic small deformation solution has been characterized by an infinite layer supported by a Winkler foundation and being axisymmetrically loaded on the upper surface. Thus the full-field elasticity solution for this problem necessitates knowledge of the foundation stiffness (k) of the Winkler foundation and the thickness of the upper layer (Dempsey *et al.*, 1991). Experimentally the k of the 3% agar gel (the Winkler foundation) was obtained by dividing the load/deformation (P/d) indentation value

of the 3% agar gel by the cross-sectional area of the indenter. It was previously found that the P/d values for a 3% agar gel were 38.8, 82.8, 184.9, 230.2, and 360.2 Nm^{-1} , respectively. The foundation stiffness (k) values are presented in Table 1. The experimental values of crust thickness (h), which are the thickness values of the upper layer, are also given in Table 1. It should be noted that the thickness of the layer of glue was measured as having a value of 0.071 mm. The layer of glue had a thickness that was almost 10 times smaller than the thickness of the thinnest fried potato crust layer. Thereby, the thickness of the layer of glue was neglected and the mechanical properties of the crust/glue layer accounted as one material in the analysis. L is the characteristic length or radius of relative stiffness. The characteristic length (L) can be numerically obtained from ($L^4 = D/k$) which is the relationship between flexural rigidity of the layer (D) and the foundation stiffness (k). The characteristic length (L) is given in Table 1. Table 1 also shows the values of L/h . The parameter L/h indicates the degree of interaction between a layer and the underlying foundation. It should be noted that D is the flexural rigidity of the layer ($D = E'h^3/12$). E' is the apparent elastic modulus ($E' = E/(1-\nu^2)$). E is the elastic modulus ($E = \sigma/\epsilon$) and σ is stress in the linear elastic regime, while ϵ is the strain level corresponding with the aforementioned stress. The Poisson's ratio of the crust layer is ν . The values for the flexural rigidity (D) of the crust for the 1, 2, 4, 7, and 10 minute fry times are 0.0384, 0.260, 0.473, 1.502, 2.865 $\times 10^{-3}$ Nm, respectively.

The elastic modulus (E) values for the crust of varied fry times were obtained from this author's previous experiments and have been quoted as 1.41, 2.67, 2.0, 3.32, and 4.0 $\times 10^6$ Nm^{-2} for the 1, 2, 4, 7, and 10 minute fry times, respectively. It should be explicitly stated that these values were obtained using the relation of $E = \sigma/\epsilon$. The values for the

apparent elastic modulus (E') of the crust for the 1, 2, 4, 7, and 10 minute fry times are 1.88, 3.56, 2.67, 4.43, and $5.33 \times 10^6 \text{ Nm}^{-2}$, respectively. These values were obtained from the relation $E' = E/(1-\nu^2)$ using the previously deduced value of the Poisson's ratio of the crust (0.5). It should be noted that the value of Poisson's ratio was qualitatively obtained and may not be accurate. The use of this improper value may have introduced a numerical error that is carried throughout the rest of this analysis. However, from a purely mathematical consideration this error would not be large as Poisson's ratio is squared in the relation $E' = E/(1-\nu^2)$. Therefore the numerical error introduced from using an inaccurate value for Poisson's ratio would not be significant.

TABLE 1.
EXPERIMENTAL RESULT OF FOUNDATION STIFFNESS (k),
CHARACTERISTIC LENGTH
(L), THICKNESS (h) AND L/h RATIO

Indenter Diameter (mm)	Fry Time (minutes)	Foundation Stiffness k ($\times 10^6 \text{ Nm}^{-3}$)	Thickness h ($\times 10^{-3} \text{ m}$)	Charact. Length L ($\times 10^{-3} \text{ m}$)	L/h
0.5	1	198	0.626	0.664	1.060
	2		0.957	1.07	1.119
	4		1.286	1.243	0.967
	7		1.597	1.66	1.039
	10		1.861	1.95	0.965
1.0	1	105	0.626	0.778	1.243
	2		0.957	1.254	1.311
	4		1.286	1.457	1.132
	7		1.597	1.945	1.218
	10		1.861	2.285	1.130
2.0	1	58.9	0.626	0.899	1.436
	2		0.957	1.45	1.515
	4		1.286	1.683	1.309
	7		1.597	2.247	1.407
	10		1.861	2.641	1.306
3.0	1	32.6	0.626	1.042	1.665
	2		0.957	1.681	1.756
	4		1.286	1.951	1.517
	7		1.597	2.606	1.632
	10		1.861	3.062	1.514
4.0	1	28.7	0.626	1.076	1.718
	2		0.957	1.735	1.813
	4		1.286	2.014	1.566
	7		1.597	2.690	1.684
	10		1.861	3.161	1.563

As stated by Olsson and McManus (1996) and Dempsey *et al.* (1991) the slope of a load-deformation curve, in the linear elastic regime, should theoretically reside between the values:

$$\pi D/L^2 \quad (1)$$

and

$$8D/L^2 \quad (2)$$

For the presentation of the experimental data, only the extremes of frying time and indenter sizes of the 125 experimental load-deformation curves are shown. Explicitly, the 1 and 10 minute fry time crust-agar specimens ('french fry composites') for the 1 and 4mm diameter indenters are shown in Figures 1 to 4. It should be noted the 0.5mm diameter indenter was dropped from this part of the analysis because there was a large degree of scatter in its data. It was determined that the use of the 1 and 4 mm diameter indenters as the extremes best shows the trends. Table 2 summarizes the experimental P/d values for all data. The theoretical lines of equations 1 and 2 are shown plotted in Figures 1 through 4. The experimental P/d values are the average slopes in the 1-4% strain level range of the indentation load-deformation curves for the 'french fry' composites of various fry times and indenter diameters. The theoretical lower and upper limits for P/d were calculated by placing the D and L values (above) for each fry time and indenter diameter combination into equations 1 and 2 respectively. The upper and lower limit P/d values for all of the fry times and the different sized indenters are also given in Table 2.

It was noted that the standard deviations quoted for the experimental data in Table 2 were high. To determine if specimen preparation procedures were responsible for the variation in the data, auxiliary experiments were performed in which five different areas on

the same crust-agar specimen were indented and load-deformation curves were generated. This was done for the 1 and 7 minute fried crusts for both the 1 and 3 mm diameter indenters. The results are shown in Table 3. Standard deviations of the corresponding force and P/d values were of the same magnitude within the same sample as they are between different samples of the same fry time and indenter diameter. These high standard deviations may be attributed to the highly variable nature of the potato (Fahloul and Scanlon, 1996; Pang and Scanlon, 1996; Voisey *et al.*, 1969). There are examples in the literature in which high standard deviations have been attributed to the variable nature of the biological materials (Gibson *et al.*, 1981; Vincent, 1982).

FIGURE 1. LOAD-DEFORMATION INDENTATION CURVE (1MM INDENTER-1 MINUTE FRY TIME)

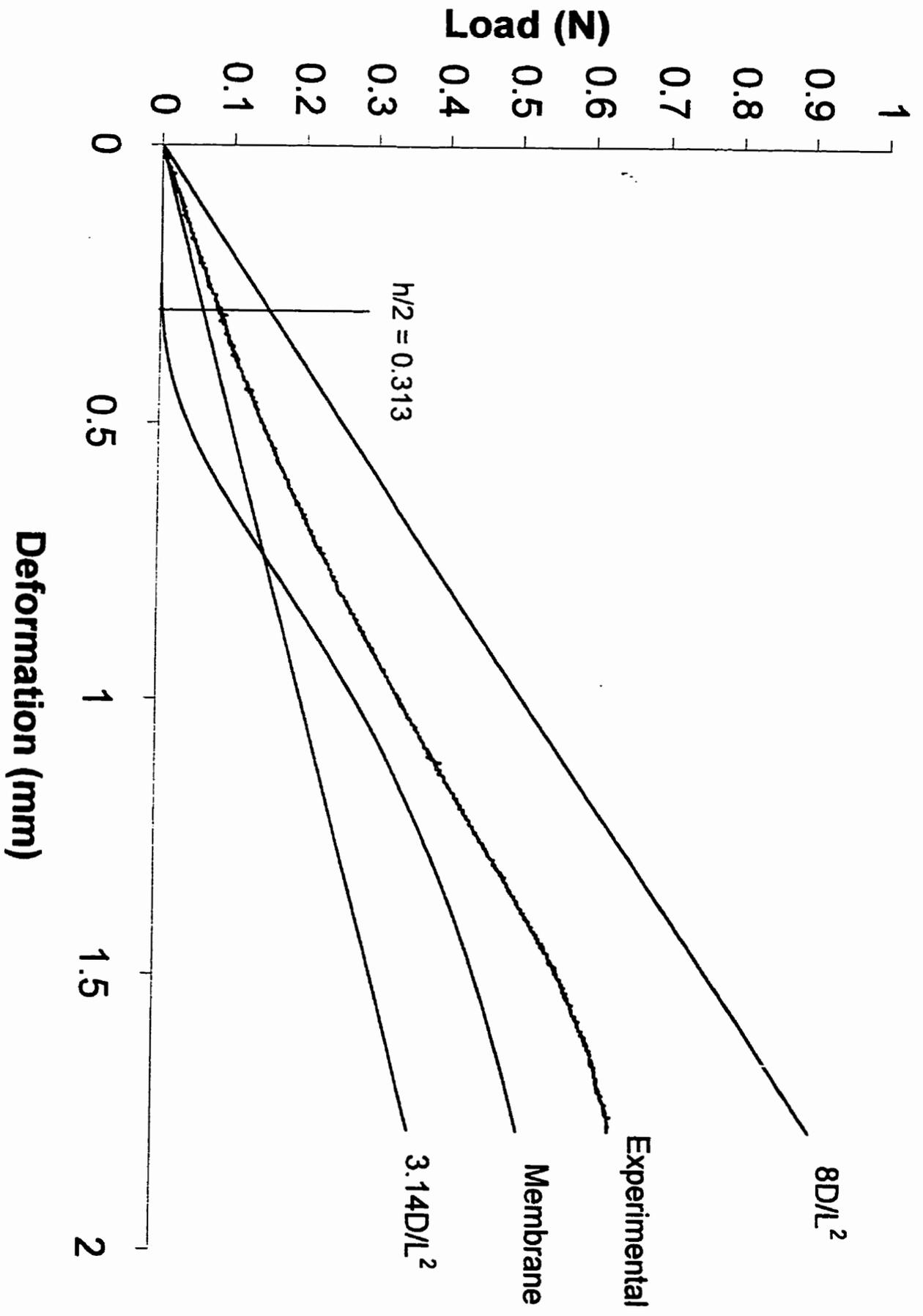


FIGURE 2. LOAD-DEFORMATION INDENTATION CURVE (1MM INDENTER-10 MINUTE FRY TIME)

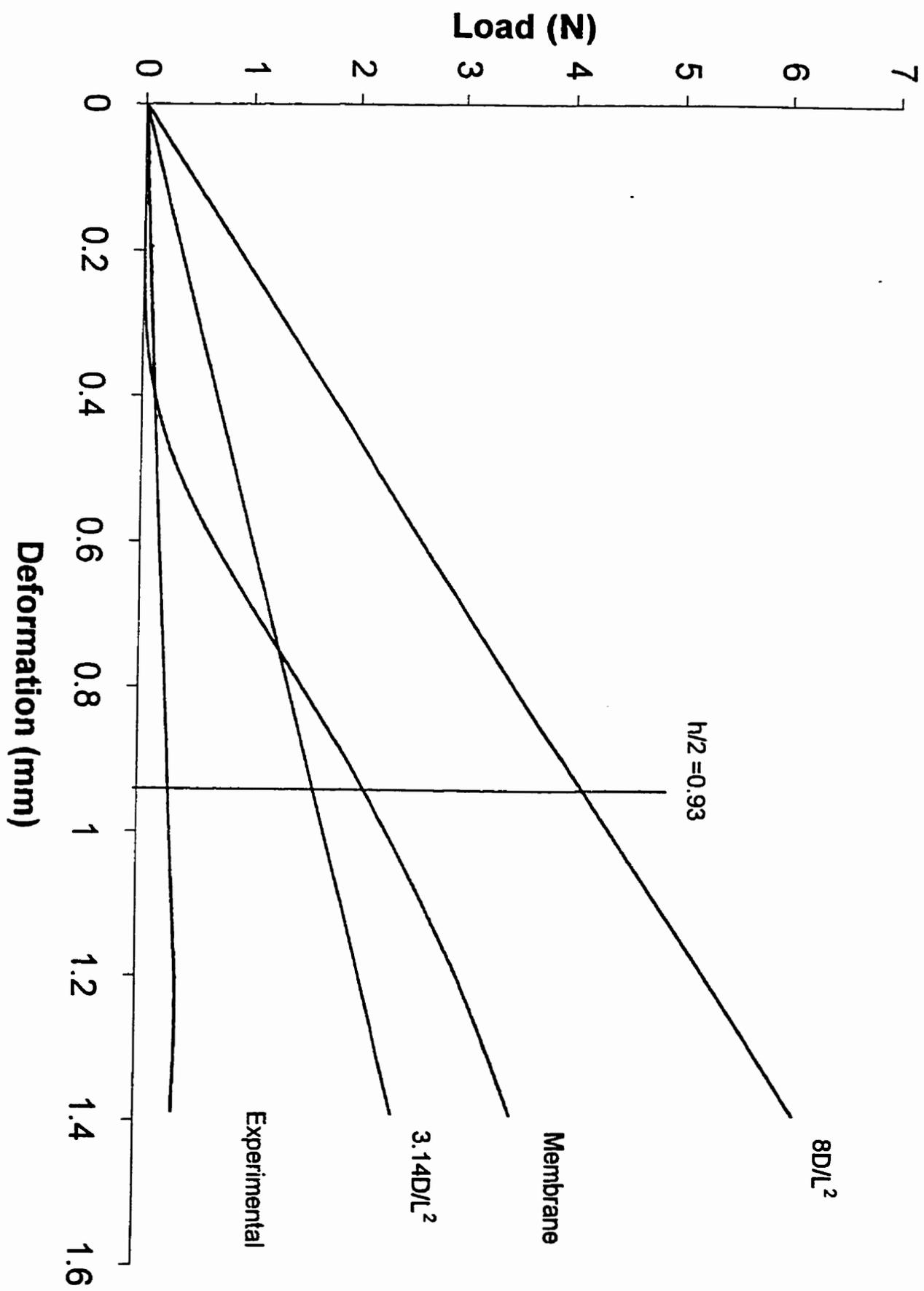


FIGURE 3. LOAD-DEFORMATION INDENTATION CURVE (4MM INDENTER-1 MINUTE FRY TIME)

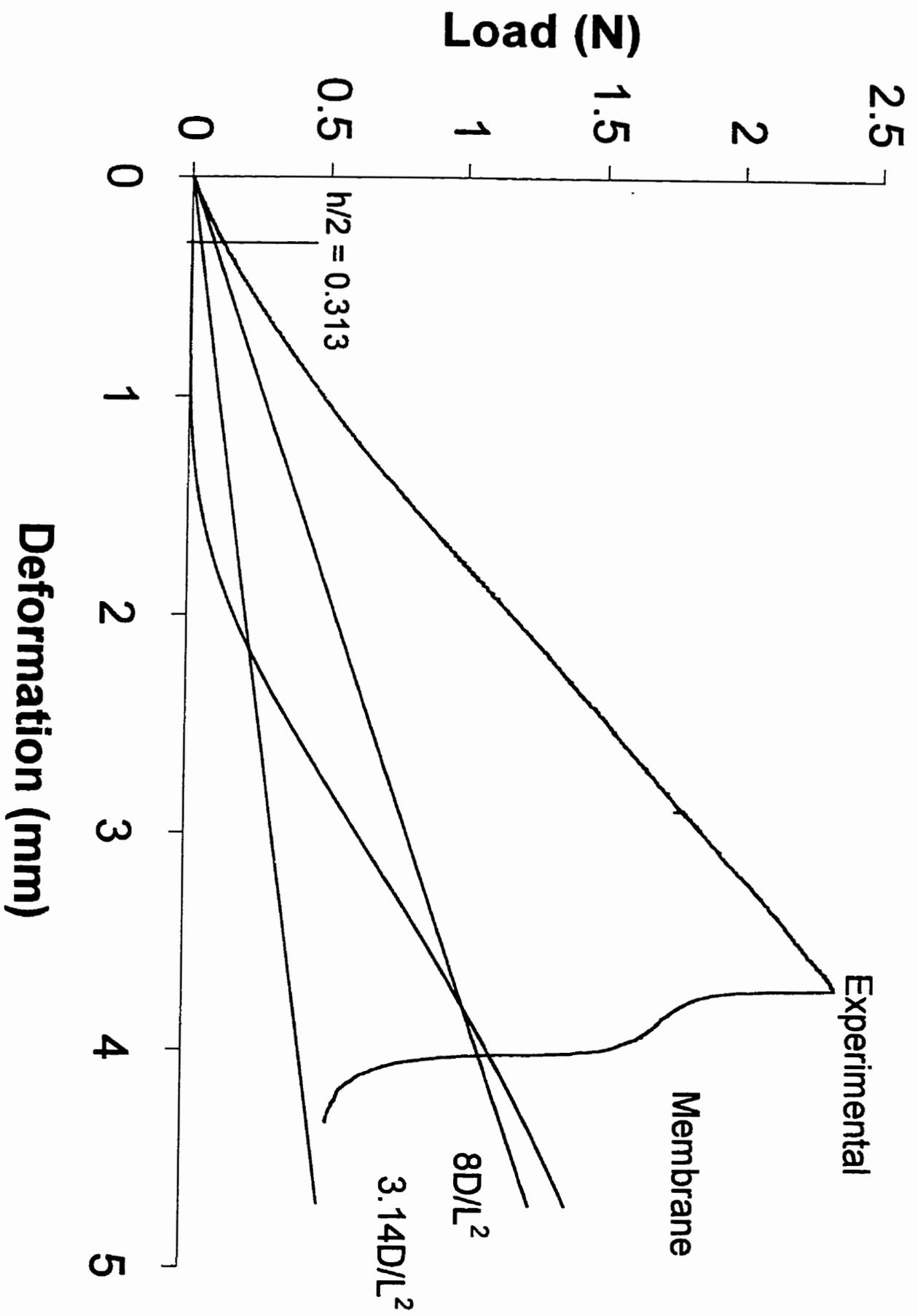


FIGURE 4. LOAD-DEFORMATION INDENTATION CURVE (4MM INDENTER-10 MINUTE FRY TIME)

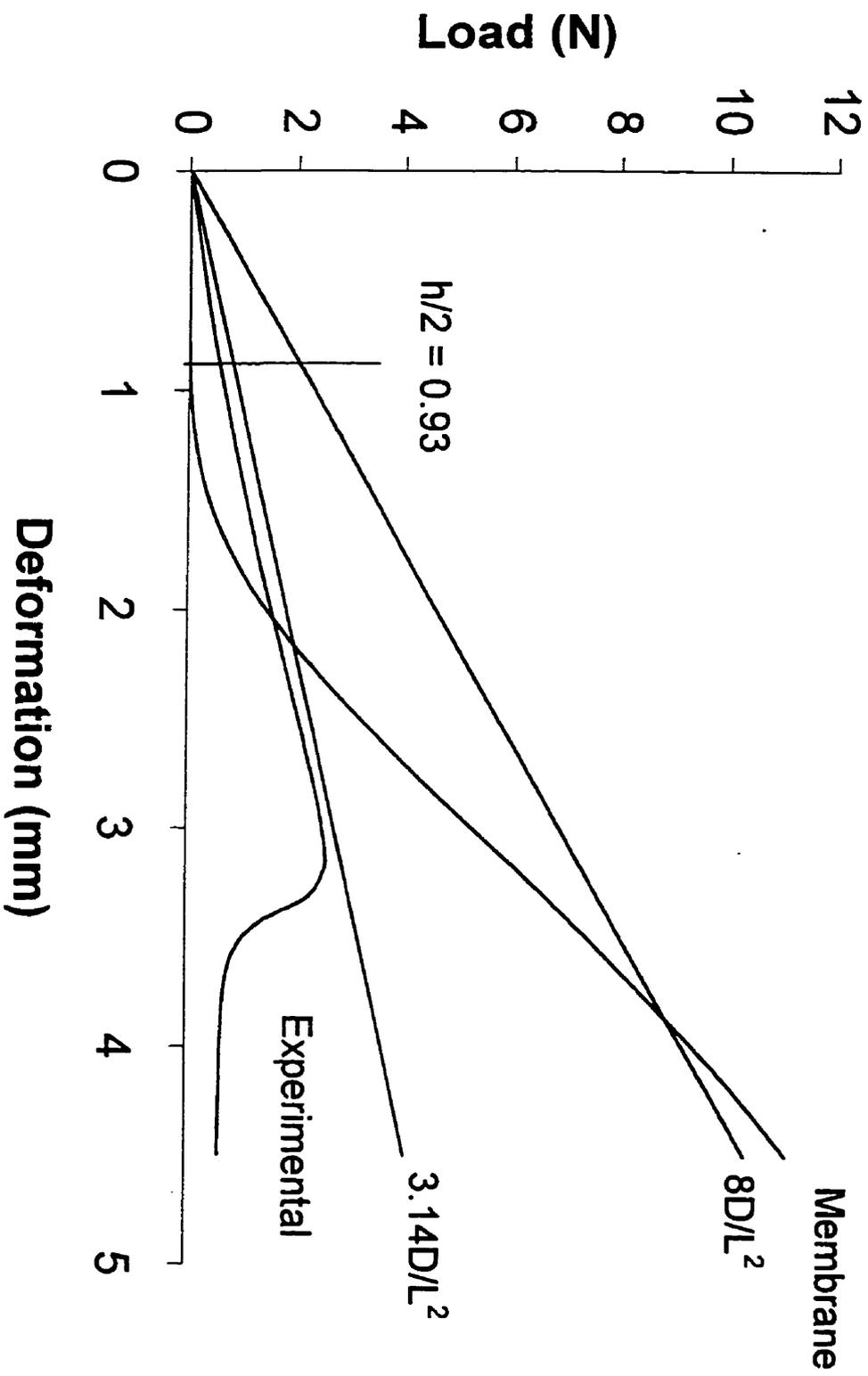


TABLE 2.**COMPARISON OF EXPERIMENTAL AND THEORETICAL INDENTATION DERIVED P/d VALUES FOR VARIOUS INDENTER DIAMETERS AND VARIOUS FRY TIMES (n = 5)**

Indenter Diameter (mm)	Fry Time (minutes)	P/d Lower Limit $3.14D/L^2$ (Nm^{-1})	P/d Experimental (Nm^{-1}) \pm standard deviation	P/d Upper Limit $8D/L^2$ (Nm^{-1})	Limit Check
0.5	1	274.04	193.12 \pm 84.31	698.19	No-below
	2	546.09	191.44 \pm 101.64	1391.30	No-below
	4	810.32	273.48 \pm 56.4	2064.52	No-below
	7	1682.14	261.75 \pm 63.03	4285.71	No-below
	10	2363.26	240.38 \pm 101.65	6021.05	No-below
1.0	1	199.29	221.56 \pm 91.21	507.77	Yes
	2	520.00	269.36 \pm 89.22	1324.84	No-below
	4	696.13	266.47 \pm 78.32	1773.59	No-below
	7	1246.03	218.70 \pm 88.52	3174.60	No-below
	10	1720.38	303.43 \pm 102.31	4383.14	No-below
2.0	1	149.26	279.40 \pm 83.70	380.29	Yes
	2	388.76	327.24 \pm 99.65	990.48	No-below
	4	521.48	311.70 \pm 95.21	1328.62	No-below
	7	932.67	424.02 \pm 102.56	2376.24	No-below
	10	1288.44	671.14 \pm 201.45	3282.64	No-below

	1	111.30	445.06 ± 105.32	283.13	No-above
	2	287.46	450.01 ± 100.78	732.39	Yes
3.0	4	387.55	476.57 ± 112.47	987.39	Yes
	7	693.67	494.39 ± 194.21	1767.31	No-below
	10	958.42	698.48 ± 209.45	2441.84	No-below
	1	104.85	433.39 ± 137.60	267.13	No-above
	2	272.13	472.75 ± 140.25	693.33	Yes
4.0	4	319.26	581.55 ± 174.34	813.41	Yes
	7	652.08	633.58 ± 189.65	1661.35	No-below
	10	900.47	771.17 ± 233.54	2294.18	No-below

TABLE 3.**THE EFFECT OF LOCATION ON INDENTATION MEASURED P/d VALUES**

Fry Time and Location of Indentation Measurement	P/d Values (Nm^{-1}) for the 1 mm and 3 mm Diameter Indenter	
	1 mm	3 mm
1 minute-middle	230	290
1 minute-top	290	380
1 minute-bottom	390	540
1 minute-right of middle	530	460
1 minute-left of middle	330	370
1 minute-average of all locations \pm standard deviation	354 ± 114.4	408 ± 95.2
7 minute-middle	220	740
7 minute-top	500	510
7 minute-bottom	430	600
7 minute-right of middle	470	810
7 minute-left of middle	330	570
7 minute-average of all locations \pm standard deviation	390 ± 114.7	646 ± 124.6

In addition to indicating the variability in mechanical properties of french fry crusts, Table 2 shows that there appears to be an indenter size and fry time interaction. At small indenter sizes, the experimental P/d values do not fit between the theoretically established upper and lower limits. This result implies that the material is as not stiff as the theory would imply. This may be due to the higher shear stresses of smaller indenters causing more plastic deformation so that the system is not adequately defined by the elastic regime. It may be that for the smaller indenters the foundation may not in fact be the agar gel but may be the crust whose k value has not been determined. As indenter size increases, the P/d values for the shorter fry times (i.e. the thinner crusts) start fitting within the theoretical

upper and lower limits. This experimental result can be supported by Dempsey *et al.* (1990) in which it was stated that the two controlling parameters in the cylindrical indentation problem are b/L (b is a true parameter for a flat ended indenter, namely, the indenter radius) and L/h . Greater values of L/h indicate either a more flexible Winkler foundation or a thinner layer; greater values of b/L , indicate a greater contact region. For these larger values of b/L and L/h , the influence of shear and transverse deformations become less significant (Dempsey *et al.*, 1990). Therefore the situation may be more accurately defined by the elastic regime. As indenter size increases the P/d values for the longer fry times (i.e. thicker crusts) start fitting within the theoretical upper and lower limits. This may seem like a contradiction in that at smaller L/h values shear and transverse deformations become more significant. However, the more important parameter of the indentation process may be the b/L ratio. In fact Table 1 indicates that L/h is roughly constant as fry time increases. From this fact, it appears that b/L is the dominant factor in determining if shear can be neglected. Therefore, as b/L increases, b increases, and the situation is better described by the more elastic solution.

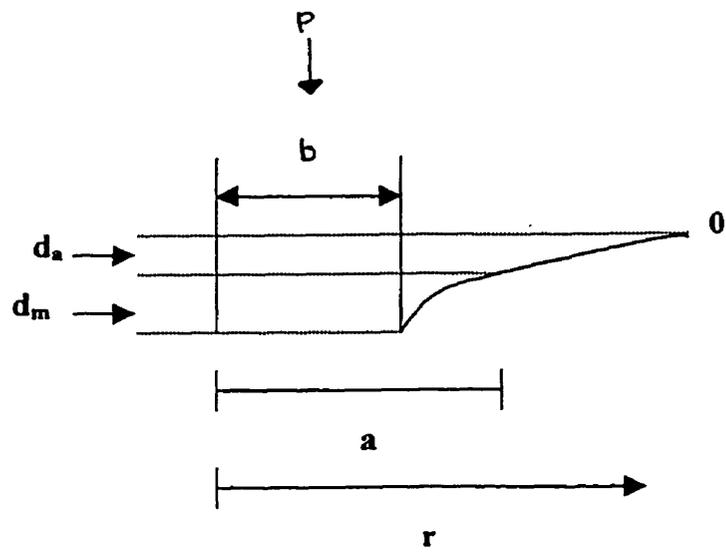
5.4.2 Non-Linear Regime

Increasing deformations increase both the magnitude and the vertical component of membrane stresses (Olsson and McManus, 1996). Deformations to a level greater than half of the upper layer's thickness causes non-linear plastic stresses to be incurred. Deformations to a level greater than the thickness of the upper layer causes non-linear membrane stresses to result. The plate theory of a layer on a Winkler foundation contains two kinds of contact: line contact, and area contact or "wrapping" (Dempsey *et al.*, 1990).

Line contact results from a point load (Dempsey *et al.*, 1990). The forces registered and deformations incurred are contained at the point of contact. Line contact occurs when indenter load and deformations are small (Dempsey *et al.*, 1990). Area contact or “wrapping” results from a constant bending moment within the contact region (Dempsey *et al.*, 1990). For line contact there is no shear force present and the upper surface contact pressure is the same as the lower surface support reaction. Outside of the contact region, deformation and shear forces follow the slope of curvature of the indenter for the contact half-length (i.e. for a cylindrical indenter this contact half-length is the indenter radius) (Dempsey *et al.*, 1990). For larger indenter, load wrapping occurs and the load deformation relation becomes non-linear (Dempsey *et al.*, 1990). Therefore significant deviations from the linear elastic small deflection solution will result when deformations to a level greater than half the thickness of the upper layer are incurred (Dempsey *et al.*, 1991) and the slope of the load-deformation curve is no longer expected to reside between $\pi D/L^2$ and $8D/L^2$. It should be explicitly stated that the non-linear deformation that takes place at deflections greater than half the upper layer thickness will consist of two deformations: deformation at the plastic radius (d_a) and deformation due to membrane stresses (d_m) (Olsson and McManus, 1996). Please refer to Figure 5. Maximum deformation occurs from the centre of the indenter outwards to the radius, or in other words, the edges of the indenter. The plastic radius deformation (d_a) depends on the yield stress of the underlying material (the foundation) and its foundation stiffness (k) (Olsson and McManus, 1996). The d_a values are obtained from dividing the yield stress of the 3% agar gel (the foundation), which was previously obtained to be 8300 Nm^{-2} , by the foundation stiffness (k). This was done for each indenter size. The d_a values obtained for

the 0.5, 1.0, 2.0, 3.0, and 4.0 mm diameter indenters were 0.049, 0.080, 0.141, 0.255, and 0.289 mm, respectively. Membrane deformation (d_m) incorporates the yield stress of the foundation and incorporates properties of the upper layer (Olsson and McManus, 1996). The shape of the resulting membrane will depend on the plastic radius (a), and therefore the size of the plastic radius will affect the membrane deformation. The use of a cylindrical indenter allows for an interesting situation to exist. If the size of the plastic radius is smaller than the indenter radius, membrane stresses cannot be incurred. Thus, as previously alluded, two situations exist in the non-linear regime. Plastic non-linear involves the situation where total deformation equals the plastic radius deformation but the plastic radius is less than the indenter radius. Membrane non-linear involves the situation where total deformation is greater than the plastic radius deformation and the plastic radius is greater than the indenter radius (Olsson and McManus, 1996) (refer to Figure 5).

FIGURE 5. CONDITIONS UNDER THE INDENTER THAT DETERMINE THE CONTRIBUTION OF PLASTIC RADIUS DEFORMATION AND MEMBRANE DEFORMATION TO PLASTIC DEFORMATION
Where; P = force, b = indenter radius, d_a = plastic radius deformation, d_m = membrane deformation, r = radius of area over which deformation occurs



For all of the fry times and all the different sized indenters the total deformation at half crust thickness exceeded the plastic radius deformation (d_a). It has previously been stated that when total deformation levels exceed half crust thickness plastic deformation is incurred (Roark, 1954). Therefore, the total deformation minus the elastic deformation (simply the value of half crust thickness) yields the plastic deformation. Since the total deformation at a half crust thickness exceeded the plastic radius deformation, the plastic deformation consists of membrane deformation. In order to obtain the load due to membrane deformation, the size of the plastic radius must be known. The plastic radius can be determined from a shape factor that can be obtained from a second order polynomial which describes the shape of a cable under a constant load per unit length (Olsson and McManus, 1996). There is a relationship between membrane deformation and the difference between the plastic radius and the indenter radius. This relationship can be described in part by the deformation shape (S).

$$S = d_m/b \quad (3)$$

Where: S is the deformation shape, d_m is the membrane deformation, and b is the indenter radius. Once the deformation shape has been determined it can be used to generate the plastic radius by the following equation (Scanlon, 1998):

$$a = d_m(2/\pi S + 1/\pi S^2) + b \quad (4)$$

Where: a is the plastic radius. It should be noted that d_m in equation 4 will have an assigned value of zero when the plastic radius is less than the indenter radius since a negative value of membrane deformation is not logical (unless adhesion occurs). A numerical fit constant (f_w^3) is necessary to obtain theoretical values of the corresponding

membrane forces in equation 6 from this plastic radius. This numerical fit constant is given by derivation of Olsson and McManus' (1996) work.

$$f_w^3 = (a-b)/b \quad (5)$$

According to membrane theory, a point load is distributed over a small area and the radius of indentation of a perfect membrane is equal to the indenter radius for a cylindrical indenter (Olsson and McManus, 1996). Therefore from further derivation of Olsson and McManus' (1996) work, it can be stated that the load due to membrane deformation (P_m) is given by

$$P_m = (2Eh/\pi a^2) f_w^3 d_m^3 \quad (6)$$

The theoretically determined P_m values were plotted against deformation values for every fry time and indenter diameter tested. Again for simplicity only these theoretically derived load versus deformation curves for the 1 and 10 minute fry times for the 1.0 and 4.0 mm diameter indenters are shown in Figures 1 through 4. It can be observed from these graphs that as the indentation process progresses and the deformation becomes greater, the non-linear membrane theoretical line more accurately depicts the indentation process than the linear small deformation theory. This is shown nicely for the 1 mm 1 min case but is a bit more difficult to defend for the 10 minute cases, although arbitrary scaling factors would bring all but the linear 4mm 10 min curves onto the membrane solutions, indicating the validity of incorporating a membrane solution in the analysis.

5.4.3 Normalizing Load Deformation Data

It is beneficial to normalize the load-deformation data as it allows of, calculation of a simple index value from which comparisons of mechanical properties of engineering materials can be made. From a food science aspect, normalization of the data also allows for a simple index value from which comparisons of mechanical properties of biological materials in terms of textural parameters can be made. The elimination of the expression of textural parameters in units makes normalization more suited to the practical nature of food processing. By characterizing composite foods in terms of normalized data, results of texture measurements could be easily compared against standard measurements as a check for compliance in terms of quality control. These normalized indices of textural quality might be independent of the actual mechanical properties of the food, as long as the characteristic dimensions (e.g., L, d_a , h) have been defined.

Normalized force (P') can be obtained from the following equation (Olsson and McManus, 1996).

$$P' = P/\sigma_0\pi L^2 \quad (7)$$

Where: P is the measured load, σ_0 is the yield stress of the foundation and L is the characteristic length (as defined above). Normalized deformation can be obtained from dividing deformation (d) by the deformation at the plastic radius (d_a)(Olsson and McManus, 1996). Figures 6 through 10 show the average load-deformation indentation curves that have been normalized for the extreme fry times (1 minute and 10 minute) for all diameter indenters. These graphs also normalize the crust thickness at the different fry times by expressing it as the d_a/h ratio. Tsang and Dugundji (1992) and Shuaeib and Soden (1997) stated that the load-deformation indentation response was affected by facesheet

thickness as more load was needed to achieve the same indentation as the facesheet thickness increased. This can be observed in the graphs and this can also be seen in Table

2. Generally, as the crust thickness increased, the P/d values increased.

FIGURE 6. NORMALIZED LOAD-DEFORMATION INDENTATION CURVE
(0.5MM INDENTER)

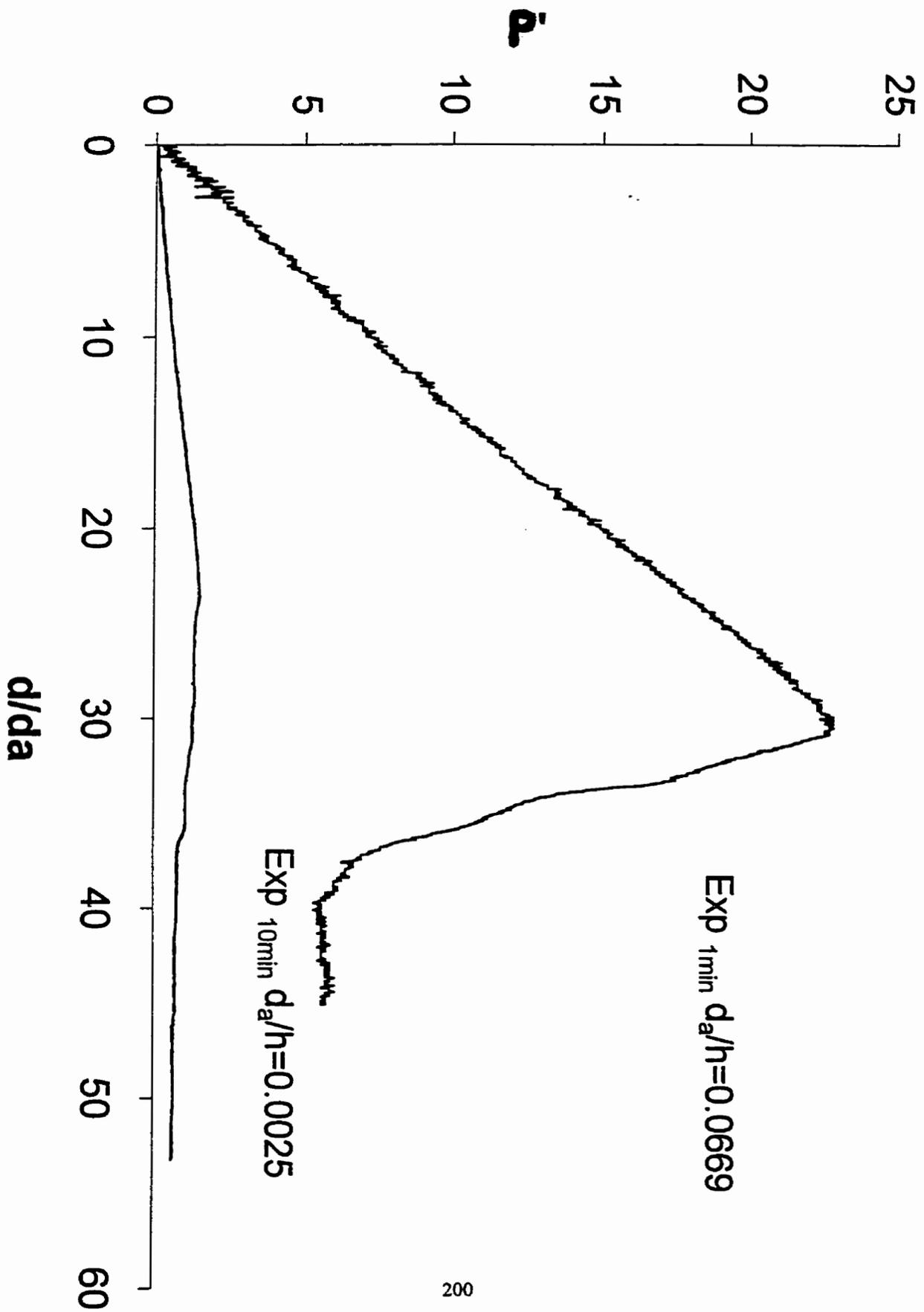


FIGURE 7. NORMALIZED LOAD-DEFORMATION INDENTATION CURVE
(1.0MM INDENTER)

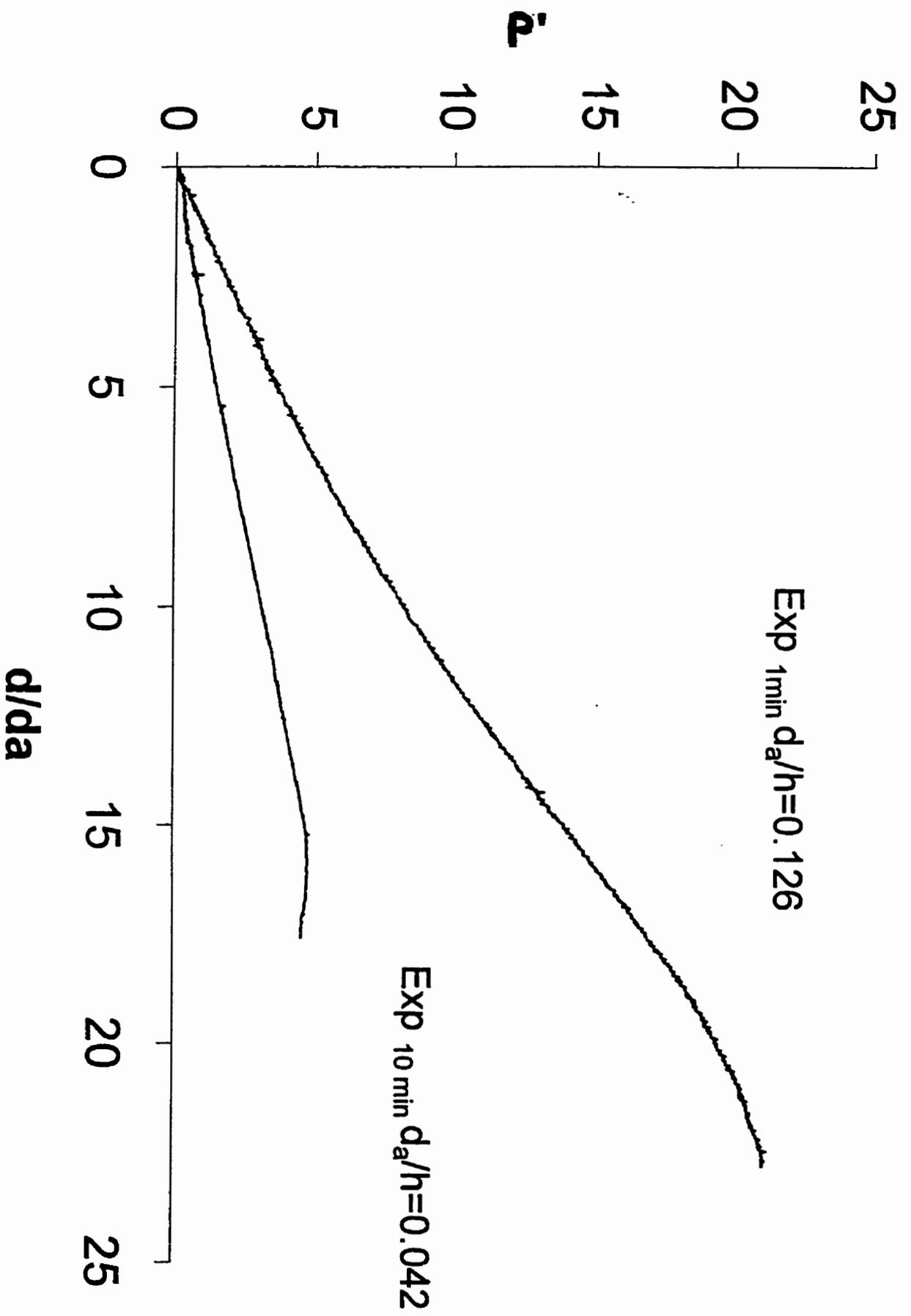


FIGURE 8. NORMALIZED LOAD-DEFORMATION INDENTATION CURVE
(2.0MM INDENTER)

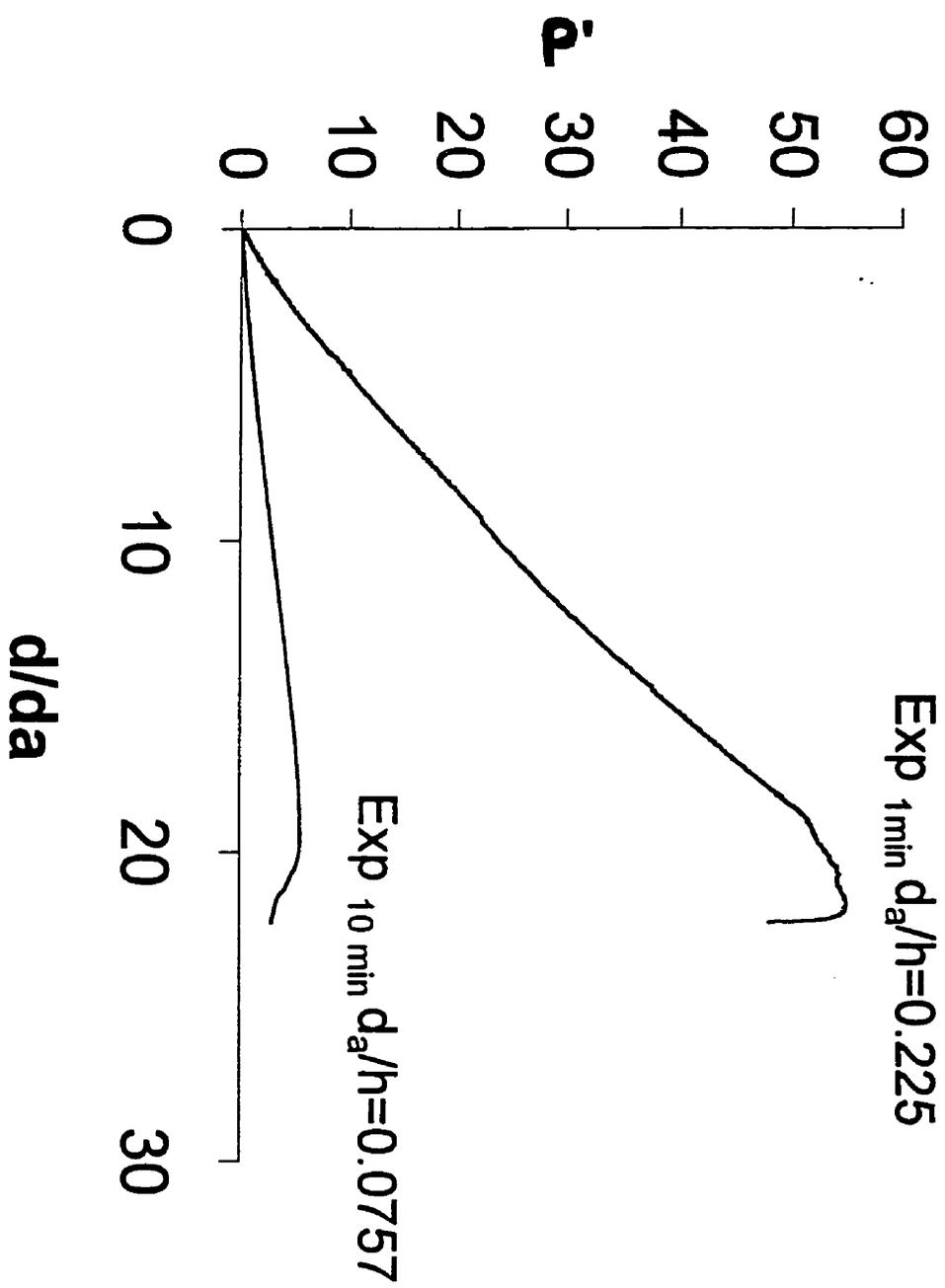


FIGURE 9. NORMALIZED LOAD-DEFORMATION INDENTATION CURVE
(3.0MM INDENTER)

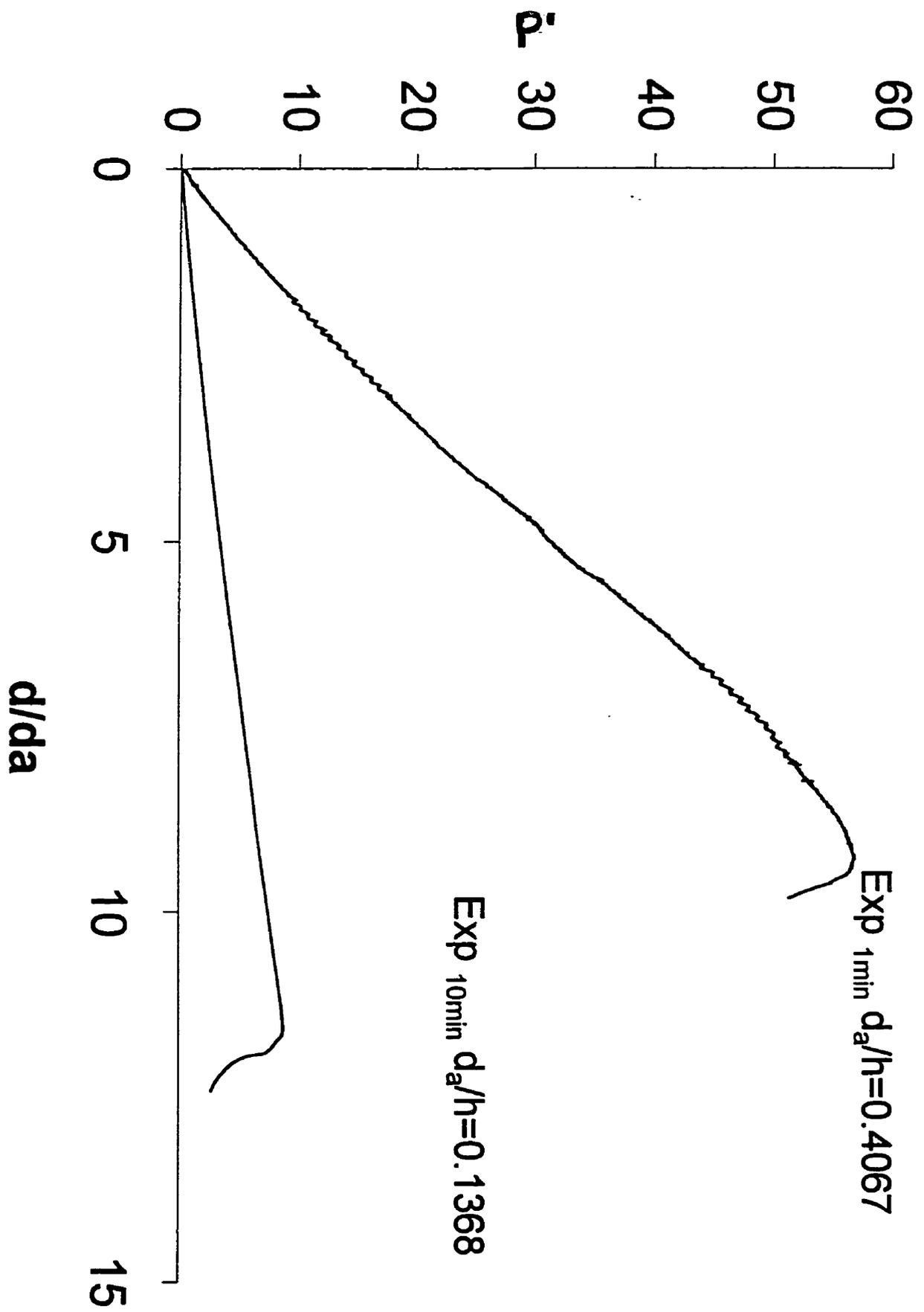
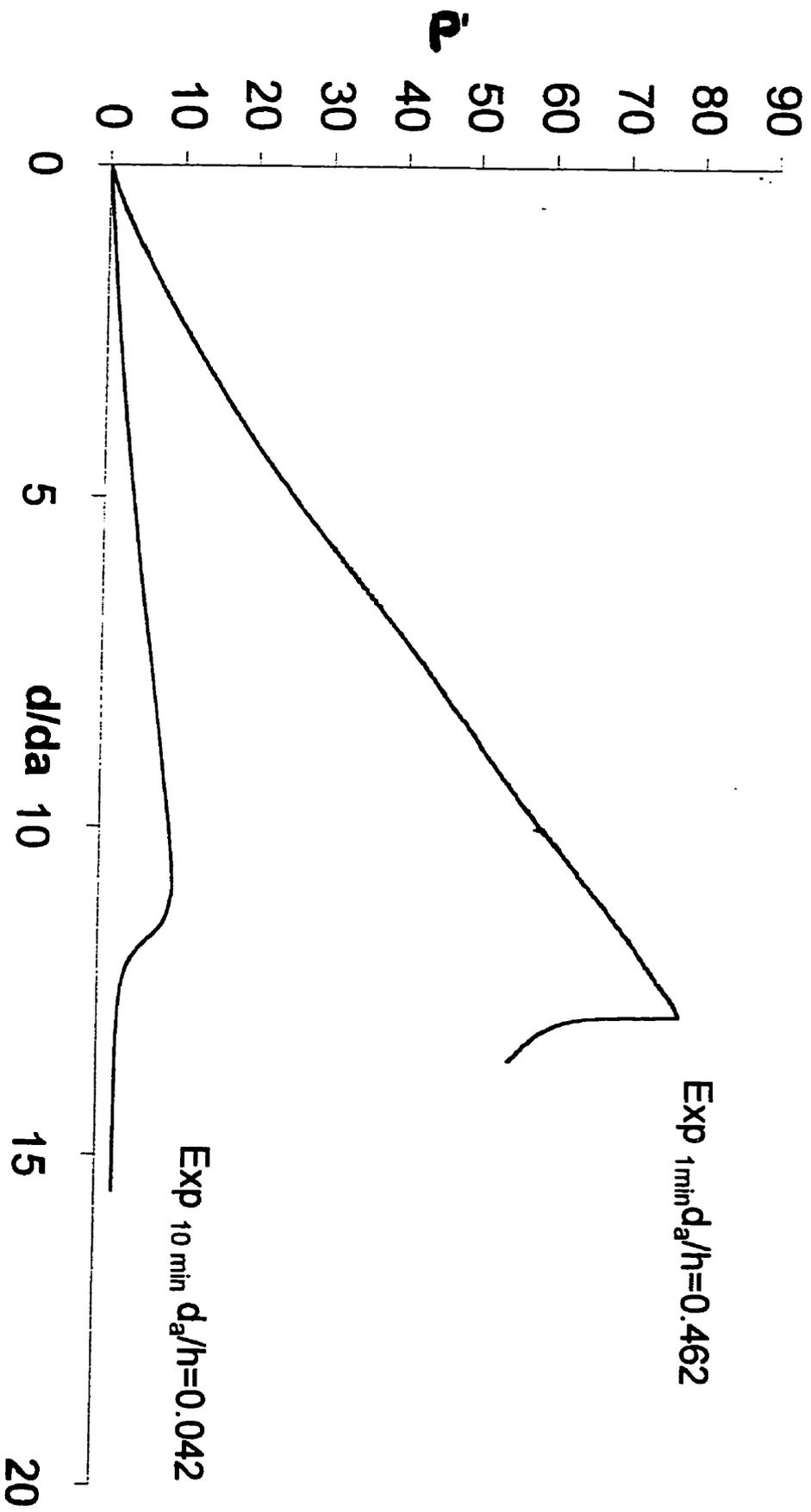


FIGURE 10. NORMALIZED LOAD-DEFORMATION INDENTATION CURVE
(4.0MM INDENTER)



5.4.4 Fracture Work

For completeness fracture stress values for the 'french fry' composites have been given in Table 4. As the indenter size increased, the fracture stress values decreased within each fry time. The fracture stress values of the 'french fry' composites for all fry times for each indenter diameter were compared to the yield stress values for a 3% agar gel (Chapter 3, Table 3). All of the composite 'french fries' have fracture stress values that are approximately 5-10 times greater than the 3% agar gel for corresponding indenter diameters. From this result it can be stated that the fried potato crust definitely contributes to the mechanical properties of the 'french fry' composite. Within each indenter diameter there seems to be no clear trend of fracture stress values increasing as fry time increased. It has been stated by DuPont *et al.*, (1992) and found experimentally in Chapter 4 (See Section 4.1.1.1) that as fry time increases the mechanical properties (of which fracture stress is an example) increase. The fact that there is no clear relationship between fracture stress values of the 'french fry' composite and fry time like there is with yield stress values of the fried potato crust and fry time seems to indicate that the common underlying foundation of the agar gel also contributes to the mechanical properties of the composite. These results illustrate the complexity encountered in measuring the mechanical properties of composite materials. However, with further study knowledge of how the crust and core interact, in terms of b/L , L/h , and d_a/h , can assist potato processors in reducing the complexity encountered in obtaining textural measurements.

TABLE 4.**FRACTURE STRESS (\pm STANDARD DEVIATION) VALUES OF THE 'FRENCH FRY' COMPOSITE FOR THE VARIOUS INDENTER SIZES ($n = 5$)**

Fry Time (minutes)	Fracture Stress (MNm^{-2})				
	Indenter Diameter				
	0.5	1.0	2.0	3.0	4.0
1	1.29 ± 0.41	0.803 ± 0.22	0.367 ± 0.11	0.228 ± 0.07	0.187 ± 0.06
2	0.786 ± 0.24	0.605 ± 0.15	0.199 ± 0.06	0.222 ± 0.06	0.159 ± 0.05
4	2.98 ± 0.86	0.533 ± 0.14	0.207 ± 0.05	0.244 ± 0.08	0.192 ± 0.05
7	2.35 ± 0.68	0.497 ± 0.14	0.263 ± 0.07	0.179 ± 0.06	0.178 ± 0.06
10	0.668 ± 0.21	0.471 ± 0.15	0.318 ± 0.09	0.168 ± 0.05	0.203 ± 0.07

5.5 CONCLUSIONS

It was determined that a model comprising a theory incorporating small plate deformation theory (describing the linear-elastic regime of the indentation problem), plastic deformation theory, and membrane deformation theory (describing the non-linear regime of the indentation problem), which are used for analyzing the indentation process of industrial composite materials, could be applied to the characterization of the indentation process of a fried potato crust-agar gel composite. It was observed that an indenter size and fry time interaction exists in the linear regime. At small indenter sizes, the experimental load-deformation (P/d) values did not fit between the established upper and

lower limits described by the small plate deformation theory. As indenter size increased, the P/d values for the shorter fry times (i.e. the thinner crusts) started to fit within the theoretical upper and lower limits. This indicated the presence of two controlling parameters in the cylindrical indentation problem namely, b/L and L/h . At larger values of b/L and L/h , the influence of non-linear deformations become less significant and the situation may be more accurately defined by the linear-elastic regime. For the largest indenter sizes, the P/d values for the longer fry times (i.e. thicker crusts) started to fit within the theoretical upper and lower limits of the linear-elastic small plate deformation solution, indicating that the more important parameter of the indentation process may be the b/L ratio. It was observed that as the indentation process progressed and the deformation became greater, the non-linear membrane theory more accurately depicted the indentation process than the linear small deformation theory. These are important steps in analytically describing the indentation process of a biological composite and ultimately generating indices of food texture and food quality via a fundamental mechanical analysis.

6.0 OVERALL CONCLUSIONS

A fundamental mechanics approach used for obtaining mechanical properties of industrial materials can be used to obtain the mechanical properties of biological composite materials. The composite studied was fried potato crust bonded to a 3% agar gel (to simulate the interior of french fries). It was shown that indentation could measure the elastic modulus of the agar gel, allowing more food texture information to be acquired, in addition to Bourne's compression and shear coefficients, although the elastic modulus values were approximately 50% higher. The mechanical properties fracture stress, elastic

modulus, fracture strain, Poisson's ratio, and fracture toughness were obtained for fried potato crust. The two fracture mechanics techniques were used to measure fracture toughness of fried potato crust. Fracture toughness values obtained by using Andrews' generalized fracture mechanics technique (1974) were approximately 30 times than fracture toughness values obtained using a brittle fracture technique proposed by Vincent (1982). The information from these studies were applied to a model comprising a theory incorporating small plate deformation theory, plastic deformation theory, and membrane deformation which are used for analyzing the indentation process of industrial composite materials. This theoretical analysis predicted with a certain degree of accuracy the indentation response of the biological composite. Admittedly, there are some problems encountered during the measurement of the mechanical properties of biological materials with theories and testing techniques developed for analyzing the mechanical properties of engineering materials. However, once contact conditions, material inhomogeneity, and inherent biological variability are accounted for, the benefits of obtaining texture measurements and characterizing the interaction of the primary components of a biological composite in terms of mechanical parameters are great. With respect to potatoes and processed potato products, further study of mechanical properties could serve to quantify textural changes that are technologically important to the potato processing industry.

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