AN ABSTRACT OF THE THESIS OF

Johannes B. Forrer for the degree of Doctor of Philosophy in Forest Products presented on January 8, 1996. Title: Dielectric Properties of Defects on Wood Surfaces.

Abstract approved: Redacted for privacy

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Raw material costs and limited material availability and quality have created significant interest in and opportunities for the application of nondestructive evaluation techniques to improve wood processing technologies. The incentives come from the desire to 1) manufacture the highest valued product, 2) conserve the amount of raw material used, 3) use lower priced and often, lower quality raw materials, and 4) meet future demands for wood products in an economy with stark contrasts of a declining wood supply and increasing pressure from environmental concerns.

Developing appropriate non-destructive evaluation techniques requires research and development of new concepts and extending the usability of known principles. Dielectrics is one such technique that offers a number of potential applications in areas such as moisture detection, drying and re-drying, grading and sorting, defect detection, curing and gluing of engineered products, repairing and patching of laminated panel products, monitoring of adhesive curing, and manufacturing of aligned fiber products.

The objective of this research was to fill the void in knowledge that existed about the dielectric properties of typical features found on Douglas-fir (Pseudotsuga menziesii) wood. Features investigated included clearwood, various sizes of loose and tight knots, knot holes, pitch pockets, pitch streaks, and blue stain. The dielectric constant and loss tangent were analyzed on a global (whole-feature) basis under a range of excitation frequencies and moisture content conditions typically found in wood processing.

This research required the development of specialized instrumentation, because measuring the dielectric properties of wood over a broad full range of moisture and excitation frequency conditions is particularly challenging. Results suggested that there are optimal combinations of moisture and excitation frequencies suitable for applications where it is necessary to distinguish between certain wood features. Simple classifications of features measured at such optimal working conditions are presented in addition to global data on the expected dielectric properties of each feature. These results form a fundamental basis for the development of future stand-alone, dielectric-based applications or applications using dielectric-based in conjunction with and other sensing methods.

Dielectric Properties of Defects on Wood Surfaces

by

Johannes B. Forrer

A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Doctor of Philosophy

Completed January 8, 1996
Commencement June 1996

Doctor of Philosophy thesis of Johannes B. Forrer presented on January 8, 1996

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

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Johannes B. Forrer, Author

ACKNOWLEDGEMENTS

I consider myself fortunate to have had the opportunity to study wood physics at such a basic level as was done in this research project. Not only did this present opportunities to develop innovative instrumentation but also laid the groundwork for much-needed future applications in this field.

My gratitude goes to Dr. James W. Funck, major professor, who guided me through the research. His attention to detail and thoroughness continually challenged and encouraged ideas that, at the time, appeared to be impossible but proved to make valuable contributions. Dr. Thomas G. Dietterich, minor professor, taught me contemporary computer science that proved to be useful in this research as well as my future career. Dr. David A. Butler exposed me to the finer art of mathematics, logic and programming. Dr. Charles C. Brunner shared his knowledge of wood and wood processing technology. Dr. Douglas F. Barofsky, graduate school council representative, provided stimulating ideas and thoughts.

I also wish to express my gratitude toward several individuals that made this study possible: Brett Matzke, Department of Statistics, for valuable suggestions on the statistical analysis method; Alberto Maristany on using SAS; David LaFever who machined the parts for the instrumentation; and Rand Sether for crafting the wood samples used in the research. Dr. Richard Holbo provided expertise, test equipment and electronic components. Dr. James B. Wilson was a constant source of encouragement.

Last, but not least, I wish to thank my family and especially my wife, Annette, for encouragement and moral support.

This thesis is based on work supported by the Cooperative State Research Service, U.S. Department of Agriculture, under Agreement No. 93-37102-9482. This financial support is gratefully acknowledged.

TABLE OF CONTENTS

Page

TABLE OF CONTENTS (Continued)

Page

TABLE OF CONTENTS (Continued)

LIST OF FIGURES

LIST OF FIGURES (continued)

LIST OF FIGURES (continued)

Figure | Page

LIST OF TABLES

LIST OF TABLES (continued)

LIST OF APPENDIX FIGURES

LIST OF APPENDIX FIGURES (continued)

LIST OF APPENDIX FIGURES (continued)

LIST OF APPENDIX FIGURES (continued)

LIST OF APPENDIX FIGURES (continued)

LIST OF APPENDIX FIGURES (continued)

Figure | Page

LIST OF APPENDIX FIGURES (continued)

Figure | Page

LIST OF APPENDIX FIGURES (continued)

Figure | Page

LIST OF APPENDIX FIGURES (continued)

Figure | Page

LIST OF APPENDIX FIGURES (continued)

Figure | Page

APPENDIX TABLES

Dielectric Properties of Defects on Wood Surfaces

1. INTRODUCTION

Raw material costs and limited material availability and quality have accelerated interest in nondestructive evaluation techniques for wood, with some sensors being dielectric based. Previous research on the dielectric properties of wood concentrated on clear wood or specific chemical components of wood. Practice, however, requires data not only on the dielectric properties of normal wood but also of typical features and defects found on wood. Expanding the dielectric properties knowledge base has become increasingly important.

A major impediment to the investigation of the dielectric properties of wood defects has been the lack of suitable instrumentation. The challenges posed in developing such instrumentation is the dynamic range involved and achieving acceptable accuracy. A device proposed by Ichijo (1953), appeared to have the potential to be extended to cover a frequency range to 50 MHz.

The research reported in this thesis comprised two experiments because of the potentially large amount of data associated with even a modest experimental design. The first experiment extensively explored instrumentation accuracy over a breadth of radio frequencies and moisture contents but was limited to a small sample set. The second experiment then used an extensive sample set but was limited to specific frequencies identified as being best in the first experiment. In addition, the first experiment explored the possibility of making distinctions between certain nontrivial wood features. These results were useful in planning which features to include in the second experiment.

Frequency and moisture content interactions were investigated for both the dielectric constant and the loss tangent. Results were used to develop a simple classification scheme to summarize the ability to distinguish between the various features.

2. LITERATURE SURVEY

2.1 Why Dielectrics? - Significance and Rationale

Before the widespread use of modern polymers (such as polyethylene, polycarbonates, polyacrylics, or Teflon®) wood and wood-based products were frequently used in electric and electronic products. This included paper insulation wrapping, paper-dielectric capacitors, impregnated wood insulators, and as a major constituent in electronic panel products such as Bakelite®. Some earlier interest in the dielectric properties of cellulose was probably due to the use of large quantities of paper in the manufacture of paper capacitors. This includes some work by Calkins (1950) and Miller and Hopkins (1947) that showed that the dielectric loss in paper dielectrics is strongly influenced by its lignin and hemicellulose content.

The use of RF energy in wood products processes includes curing wood and wood-based products, gluing of wood joints, laminating wood-based products, repairing composite panels, and veneer re-dry operations. Examples of these are described by Beall et al. (1966), Bierwirth and Hoyler (1943), Brown et al. (1947), Carruthers (1962a, 1962b, 1963), Cole and Roscoe (1957), Dimond (1948), Dunlap and Bell (1947), Fessel (1956), Gefahrt (1961, 1963, 1965, 1967, 1970), Miller (1948, 1962, 1966), Peterson (1951a, 1951b), Pungs and Lamberts (1954), Torgovnikov (1990), Vodoz (1957), and Yavorsky (1951). Most of these applications use RF energy in the 1 MHz to 30 MHz range.

Dielectric principles have found application in instrumentation for process and quality control. This includes dielectric moisture sensors such as those described by Busker (1968), Dennis and Beall (1977), Edlefsen (1933), James and Boone (1982), James (1983, 1986), Lowery and Kotok (1967), and Suits and Dunlap (1931). Busker, James, and Edlefsen described the use of microwave testing methods, while Dennis and Beall used high frequency energy. Although both techniques use electromagnetic waves, the interaction with the material's physical-chemical components is different. James covered the application of low frequency (less than 2 MHz, mostly in the kilohertz region) for moisture detection and control of lumber dry kilns.

In the area of defect detection, nondestructive testing, and stress grading, some innovations that employ dielectric principles and computer technology have been described by Bechtel et al. (1991), Cramer and McDonald (1989), McDonald and Bendtsen (1986), McLauchlin et al. (1973), McLauchlin and Kusec (1978), Norton et al. (1974), Rice et al. (1992), Samson (1984, 1988), Steele et al. (1990), and Swanson et al. (1993). Those approaches all used non-contact, in-plane dielectric sensors for slope-of-grain detection and operated at a frequency in the 500 kHz region. In comprehensive overviews of nondestructive methods for defect detection in lumber, Szymani (1984, 1985) and Szymani and McDonald (1981) summarized the advantages and disadvantages of optical, ultrasonic, X-ray, nuclear magnetic resonance (NMR), nuclear, and microwave sensing methods. They concluded that optical methods showed clear advantages, but no single methodology by itself would be sufficiently comprehensive. Szymani and McDonald went on to suggest that a combination of sensing technologies might provide complementary information. This is not surprising given, for instance, that the radio-frequency portion of the electromagnetic spectrum covers the equivalent of 21 octaves, while the entire spectrum of visible light only covers one octave. In addition, the shortest radio wave is 10,000 times longer than light waves. Therefore, all these approaches are influenced by different physical aspects of solid materials.

There has also been some limited success in the application of wood dielectrics for wood quality assessment. Shigo (1977) initiated interest in this technology as a means for detecting the state of decay in wood. Kawaguichi et al. (1988) give a review of instruments for this purpose, while applications of this type of technology are described by Piirto and Wilcox (1978).

Dielectric principles are also used in the manufacture of oriented particle boards as described by Pulido et al. (1991). The ability to polarize dry, lightweight wood particles electrostatically allows for a certain degree of mechanical manipulation of the particles.

2.2 Definitions and Background

When non-conductive materials are placed between parallel electrodes in an alternating current (AC) circuit, polar molecules in the materials attempt to align themselves in the electrical field. At direct current (DC) or low AC frequencies, disassociation of ions in the material may occur that may lead to the migration of ions toward the electrodes. For wood, such ionic mobility has been studied extensively for application in conduction-based wood moisture meters. This research, however, is aimed at higher frequencies, where field reversals are so rapid that little or no ionic migration takes place. Polar effects thus predominate and have a strong influence on dielectric constant; however, the material's molecular structure also gives rise to electrical conduction phenomena.

As the polarity of the applied voltage changes, molecular rotation attempts to follow the changing field polarity, but will exhibit a certain degree of lag. The changing field within the dielectric material is thus slightly out of phase with the energizing field. In addition to the polarization, a certain amount of electrical conduction also takes place. This kind of conduction is an instantaneous effect and is in phase with the energizing field. Thus, two sources of Joule heat are generated: (1) friction effects due to the molecular rotation and (2) ohmic heating due to conduction.

A vector diagram is best used to represent the effective current in the dielectric in terms of the in-phase and out-of-phase components. The angle Θ, between the effective current and the in-phase component, is called the phase angle. The quantity, $\cos\Theta$, is called the power factor. The loss angle, $\delta = (90 - \Theta)$, is related to the power loss in the dielectric. The quantity $\tan\delta$, commonly known as the loss tangent, is the ratio of power dissipated to the total power over a full AC cycle.

The in-phase and out-of-phase current relationships may also be expressed as the real and imaginary components of the total effective current in complex mathematical notation. Thus, using complex mathematical notation, the dielectric constant is then defined as a complex quantity:

$$\epsilon^* = \epsilon' - j\epsilon''$$

where:

the real part, ϵ', is the dielectric loss,

the imaginary part, ϵ'', is dielectric constant,

and $j = \sqrt{-1}$.

Further, $\tan\delta = \epsilon''/\epsilon' = 1/Q$. The quantity "Q" is called the quality factor as it relates to the amount of energy dissipated over a full AC cycle. Thus, a low Q would imply higher energy dissipation than for example high Q values. The dielectric parameters, $\tan\delta$, ϵ'', and ϵ' all depend on frequency, *f*. The properties of a dielectric may thus be fully specified by $\epsilon'(f)$, $\epsilon''(f)$, or by $\tan\delta(f)$ and $\epsilon'(f)$.

An interesting general overview of the development of dielectrics is provided by Henson and Hassler (1963). They show that inadequate theory and techniques led to a very active period between 1925 and 1940 when several biophysicists applied potential theory originally developed for dielectrics. About 1935, investigations began into the electrical properties of protein molecules using the concept of polar molecules originated by Debye (1929). After 1940, techniques became available for investigation of electrical properties at ultra high and low frequencies. The frequency range then explored, extended across almost ten decades (5 Hz up to 30 GHz) instead of four decades (1 kHz to 10 MHz) available before 1940. Subsequently, considerable interest has been shown concerning electrical properties of biological materials of interest in agricultural processing.

The work of Debye (1929) is generally considered as a landmark contribution toward an understanding of polar behavior, while the contribution of Cole and Cole

(1941) provided further generalizations of this theory to better explain experimental observations. MacDonald (1987) showed renewed interest in dielectric spectroscopy due to the availability of advanced impedance analyzers.

Several text books on dielectrics have proved useful in this study including Miner (1941), Brown et al. (1947), Hartshorn (1949), von Hippel (1954, 1961), Smyth (1955), Frohlich (1958), Anderson (1964), Harrop (1972), Jonscher (1983), and Torgovnikov (1993).

2.3 The Dielectric Properties of Wood

Nanassy (1970) describes the electrical properties of wood in terms of a material that is opaque, inhomogeneous, amorphous, anisotropic, and hygroscopic and has a complex and indefinite molecular structure. Some problems arising from the use of wood remain unanswered due to limited knowledge of the physical properties of wood at the molecular level. It is in the interest of the wood processing industry to develop a better understanding of such basic physical properties, especially to gain insight into the electrical interface of wood, as many wood processing problems depend heavily on such technology.

It is convenient to divide the literature on the dielectric properties of wood into two broad categories: that dealing with the explanation of dielectric behavior at the molecular level, and that dealing with the application of dielectric behavior at a macromolecular level. The level of detail and methodology between these approaches differs significantly. Most applications of dielectrics at the macromolecular level deal with wood processing problems at an engineering level.

For this purpose, dielectric behavior is then defined in terms of engineering power measures, such as power factor, loss factor, reactance, capacitance, and electrical conductivity, with lesser emphasis on the exact nature of the dielectric behavior. Even at this level, the extreme range in electrical properties of wood from its green to its dry state often leads to engineering difficulties. For example, wood in its green state is extremely conductive and exhibits a large dielectric constant due to the presence of water. Wood in this state appears as a shunt to high frequency current. In its dry state, on the other hand, wood has low conductivity and a low dielectric constant. In fact, this property is common knowledge since wood is well known as an excellent electrical insulator. The development of an instrument that has to measure such a range in properties with good accuracy and repeatability is challenging.

The causes for the polar behavior of wood have been researched by Anagnostopoulou-Konsta et al. (1989), using a thermally stimulated depolarization current method (TSDC); They showed that there are at least three different polarization mechanisms present in wood: (1) effects associated with loosely bound water in the wood structure, (2) water assisted relaxation of dipolar groups of wood constituents and/or methylol-water complexes, and (3) space charge trapped mainly in the interface between sample and electrodes. In the presence of water, the magnitude of the dipole of water to some extent obscures the dielectric spectrum of the various dipolar groups present in wood. This effect is reflected in the range of the dielectric constant for wood which extends from approximately 2.5 in the dry state to over 81, the value for water, when green. The true dielectric spectrum of woody tissue can thus only be studied with oven-dry wood.

The term "dielectric spectroscopy" refers to the behavior of dielectric materials as a function of the electromagnetic spectrum frequency and includes the range from DC to infrared. Exploration of an extended frequency range is relatively new, but has in some form or another been applied to wood by several researchers in the past (Hojendahl, 1946; Peterson, 1960; Trapp and Pungs, 1956; Poliszko et al., 1985; and Nanassay, 1964, 1970).

2.4 Factors that Affect the Dielectric Properties of Wood

To further structure this review of the literature on the dielectrics of wood, the remaining part of this literature review has been divided into sections corresponding to the main factors that affect the dielectric properties of wood; these are temperature/moisture, specific gravity/fiber orientation, frequency, field strength, and chemical composition.

2.4.1 Temperature and moisture effects

When studying wood structure using dielectric spectroscopy, it is important to realize the overpowering effect that the presence of moisture has on dielectric properties. The magnitude of the water dipole can easily mask the effects of wood constituents. For example, at 10 MHz the dielectric constants of water, green lumber, and dry lumber are 81, 38, and 2.5, respectively (James, 1975). Beldi et al.

(1968) investigated the influence of moisture content in the range of zero to 20%, frequency in the range of 50 Hz to 80 MHz, and fiber orientation for three different European oak species. They observed that one species, Quercus cerris, was distinctly different. It was suggested that this agreed with that species' mechanical properties being different than the other species. The consensus was that moisture content and frequency interacted in a complex fashion. Magnitudes of both dielectric constant and loss factor were greatest in the kilohertz frequency region, relatively constant in the high frequency region, and increased slightly above 30 MHz. The magnitude of the dielectric properties increased with an increase in moisture content.

Lin (1973) found indications that there are possibly three different moisture bonding mechanisms. These were shown by Lin as discontinuities in the moisture content - dielectric constant relationships. The three regions were identified as corresponding roughly to oven-dry to near 8%, 8% to 40%, and above 40% moisture content. From a theoretical physics perspective, he pointed out that 8% moisture content corresponds to a desorption stage where each sorption site is bonded to a single water molecule. For adsorption the corresponding point occurs at 6%. Norimoto and Zhoa (1993) explored these phenomena and suggested that sorbed water below approximately 10% EMC (60% RH at 20°C) was probably due to a monolayer and scission of two hydrogen bonds. Above 10% EMC, multiple hydrogen bonds were involved.

The effect of temperature further complicates the interaction between frequency, moisture content, and dielectric parameters. This is shown in the work of Nanassy (1970) and Trapp and Pungs (1956), where the effects of frequency and temperature were investigated on oven-dry wood. This work showed the existence of weak, but distinct, maxima for the loss factor. The magnitude of these maxima is dependent on frequency, and the location of the peak shifted to different frequencies at different temperatures. These maxima for the loss factor are also described by Skaar (1948), Norimoto and Yamada (1969), Norimoto (1970, 1976), Torgovnikov (1990), and Tsutsumi (1966, 1967). In contrast, Rafalski (1966, 1967) could not detect such loss factor maxima on compressed beach wood. This could possibly be due to modification of the wood structure during plastization processing.

Giessen and Du (1995) found that wood, subjected to prolonged periods of heating in dry kilns, undergoes slight changes in its DC electrical properties. They attributed this change to the breakdown of hemicelluloses into lower molecular weight organic acids thus increasing ionic concentration. For instance, drying at 90°C for 90 hours resulted in a 2.18% higher moisture content reading than expected by the electrical conduction moisture meter. It is expected that such prolonged temperature treatment of wood would also affect AC properties.

2.4.2 Specific gravity and fiber orientation effects

It is generally accepted that the specific gravity of wood influences its dielectric properties. Skaar (1948) and Hearmon and Burcham (1954) suggested there was a correlation between dielectric constant and specific gravity. This suggestion was supported by Uyemura (1960), where a relationship between dielectric constant and specific gravity of wood was developed. Noromoto and Yamada (1970) found that the loss factors of ten different wood species were linearly related to specific gravity in the 30 Hz to 3 MHz range for temperatures from 64°C to 31°C. The relationship between dielectric loss factor and specific gravity of wood was further described by Norimoto and Yamada (1970). They showed a linear relationship between loss factor and specific gravity for wood in the longitudinal direction. They further found that the removal of certain extractives in alcohol and benzene solutions did not effect the behavior of the loss factor. However, Hearmon and Burcham (1954) could not show any definite relationship between loss tangent and specific gravity for air-dry wood.

The influence of specific gravity on dielectric properties in terms of an orthotropic model was researched by Norimoto (1970) and Torgovnikov (1990). Norimoto (1971) and Norimoto et al. (1978) presented a comprehensive model to describe the dielectric behavior of wood that was based on several anatomical parameters such as fibril angle, cell wall thickness and shape, and theoretical values for dielectric constants for wood constituents (i.e., cellulose, hemmicelluloses, and lignin). It is believed that these parameters also define the specific gravity of wood. Some uncertainties result, however, because the exact microstructure of wood is not known.

Lin (1973) also proposed an orthotropic model of wood dielectric behavior that he tested on Western hemlock (Tsuga heterophylla). He found that experimental data matched such a model below 15% moisture content. Lin also found that the within-sample specific gravity variations of his Western hemlock samples were not statistically significant and thus could not be included as a factor in his orthotropic model that included moisture content. He stressed, however, that when dealing with different wood species, specific gravity differences between species should be taken into account.

Certain dielectric-based wood moisture detection equipment use an empirical "species correction". Such adjustment is required for a particular wood species where both specific gravity and chemical composition affect dielectric properties. This may be due to the fact that dielectric properties are affected by the amount of polarizable substance per volume of material, whereas specific gravity is the amount of mass per volume without regard to polar material. An appropriate procedure is described by Hughes et al. (1963) where a radioactive density gauge is used to compensate for specific gravity effects.

The effect of fiber orientation on the dielectric parameters is due to the anisotropic nature of wood and is maximum along the longitudinal axis. The magnitude of the dielectric properties in the radial and tangential directions are slightly lower. In particular, the ratio between the longitudinal and transverse directions has been given as ranging anywhere from 1.5:1 (Samson, 1984; Skaar, 1948) to 1.33:1 (Norimoto, 1976) to 1.2:1 (McLauchlan et al., 1973). The lower ratio of dielectric properties in radial versus tangential orientation is attributed to the presence of rays. Torgovnikov (1990) found that for wood species containing up to 12% ray material, a ratio of 1.04 - 1.05:1 in the frequency range of 10^2 to 10^8 Hz and a ratio of 1.02:1 in the frequency range of 10^9 to 10^{11} Hz existed for the dielectric constant. For the dielectric loss, the ratios were 1.06 - 1.09:1 and 1.04 - 1.05:1 respectively. However, for wood species with ray contents between 20 and 28%, the ratios were 1.08:1 for the frequency range of 10^2 to 10^8 Hz and 1.04:1 for the frequency range of 10^9 to 10^{11}. The corresponding ratios for dielectric loss were then 1.19:1 and 1.10:1 respectively. These differences served as a basis for Torgovnikov's dielectric tensor model for wood. Rafalski (1966, 1967) found similar ratios for beach wood, i.e., ratios of 1.05:1 for the dielectric constant and 1.14:1 for loss factor between radial and tangential directions of beach wood in the 0.2 to 25 MHz frequency range.

Kroner and Pungs (1949) and Uyemura (1960) suggested that these anisotropic characteristics resulted from cell wall orientation rather than from microscopic structural differences in wood. Skaar (1948) and Hojendahl (1946) theorized that orientation and fiber length may influence the molecular structure of the cell wall. Because orientation of the cellulose axis is approximately the same as the fiber axis, the hydroxyl groups possess more freedom along the grain than across the grain. Tanaka et al. (1975) studied the relationship between dielectric properties and the grain angle of wood and presented a relationship based on the dielectric constants in the radial and longitudinal directions. They further found that the square of the ratio of the dielectric constant in the longitudinal direction to the dielectric constant in the radial direction increased with increasing temperature and with decreasing frequency. Thus, differences in dielectric properties due to anisotropy increases with temperature and are also more noticeable at lower frequencies.

Vermaas (1973) provided a model based on empirical observations using various species of wood for predicting the dielectric constant and loss factor based on a set of regression equations that included terms for moisture content, density, frequency, orientation and resin content. This model indicated that resin content had little or no influence on dielectric properties.

2.4.3 Excitation frequency considerations

In studying the dielectric properties of yellow birch, Nanassy (1970) reported that intense dielectric absorptions existed in the low frequency region (below 500 kHz) while another absorption maximum occurred in the high frequency region (0.5 to 100 MHz). The intensity of absorption and the actual frequency location of the peak were found to be temperature dependent. At room temperature, the peak occurred between 1.0 MHz and 100 MHz. His findings further suggested a relatively smooth progression of the dielectric properties within this region. Nanassy further investigated the relationship between temperature and the frequency of the peak and found a linear relationship between frequency and the reciprocal of the absolute temperature. This is an indication of a temperature-stimulated activation process. Similar findings have been reported by Trapp and Pungs (1956) on pine and by Tsutsumi (1967) on Japanese willow woods.

It has been shown by Pyper et al. (1985), that a biological substance, such as wood, has a dielectric behavior indicative of two distinct moisture-bonding mechanisms. These mechanisms are respectively, water that is bonded to the crystalline structure and free water within the wood structure. Busker (1968) has shown that the dielectric behavior of wood pulp in the microwave region is mostly a function of the amount of free water in the wood. Therefore, unless the distribution of free water in wood is used to characterize its structure, there is some uncertainty whether microwave methods will provide sufficient resolution power for detecting wood features in wood at low moisture contents.

2.4.4 Electrical field strength effects

Nanassy (1972) also tested the influence of field strength on dielectric measurements. He found that the dissipation factor and conductivity were field-dependent in the kilohertz frequency range. These phenomena were attributed to the formation of ionic charges by disassociation and the migration of the charges over some distances under the action of an alternating current field. Rice et al. (1992) also stated the importance of field penetration aspects of different sensors for different thicknesses of wood material that is an important factor for their fringe-field sensing system.

James (1981, 1983) and James and Boone (1982) experimented with various electrode arrangements involving both through-volume and fringe-field configurations. These arrangements were typical applications and could be used with low frequency capacitance-admittance type kiln controllers. Several areas of concern relating to the wood-electrode interface with temperature and kiln atmospheres and the influence of moisture gradients within the wood were revealed. James concluded that no significant gains in reliability could be made for the added inconvenience associated with the use of through-volume measurement arrangements. Unfortunately this research did not investigate high frequency principles where the effects of both temperature and ionic disassociation are often reduced.

2.4.5 The measurement of dielectric parameters of wood at high moisture content

Ichijo (1953) and Ichijo and Arai (1961) described a device capable of measuring the dielectric properties of materials with high loss factors. Ichijo showed that this approach was suitable for use on some highly conductive semiconductors such as conductive rubber. This method can deliver the same accuracy for the measurement of the dielectric constant as the resonant method described by Hartshorn and Ward (1936). Through the usage of a double resonant device, loading effects can be isolated from the measurement circuit. Thus, this method is an attractive alternative to the classical resonant approach. There are, however, some practical constraints that need to be observed. Ichijo's simplification of certain theoretical derivations for the dielectric loss factor is based on assuming that the product $2\pi fCR$ is less than 0.1, where f is the measurement frequency, C is the value of substituted capacitance, and R is the value for substituted resistance.

It is evident that this method would not be practicable above approximately 5 MHz due to the device's internal stray capacitances and imperfection in the split-stator capacitor. In fact, Ichijo specifies a maximum frequency of 2 MHz for his device. This has been proven to be the case in practice.

2.4.6 Chemical composition effects

Dielectric behavior in solids is due to two basic mechanisms, i.e., dipolar polarization and ionic kinetics (Johnscher, 1983). It is thus appropriate to further investigate the significance of these mechanisms in wood. Nanassy (1970) showed that these basic dielectric mechanisms are evident as overlapping dispersion and absorption regions in the dielectric spectra for oven-dry yellow birch wood samples.

The main chemical components of wood that contain polarizable materials are cellulose, hemicellulose, lignin, and extractives. The cell walls of woody fibers are composed of loosely packed cellulose, embedded in a hemicellulose-polyuronide-lignin complex (Stamm 1964). Cellulose molecules are composed of Beta-D-glucopyranose units with 1-4 bonds to form a linear polymer containing OH polar groups. It is also known that cellulose comprises crystalline and amorphous portions and from X-ray spectra that the crystalline cellulose monomer is monoclinic and formed from four glucose anhydride units. Due to the proximity of primary OH groups of two different but adjacent anhydroglucose units, lateral bonds between the units are often formed through hydrogen bonding. It is believed that in the C-direction, the unit cells are bonded by dipole forces between OH groups and permanent electric moments between C-O-C groups. Electron microscopic spectra revealed that many unit cellulose cells combine into a crystallite that has a length of about 600 Angstroms and a breadth of between 50 and 150 Angstroms (Panshin and de ZeeuW, 1980). The cellulose molecules are considerably longer than the crystallites so that a single cellulose molecule passes through several crystallites and amorphous zones.

According to Nanassy (1972), the work of Muus (1953) suggested that dielectric absorption in the 0.1 MHz to 100 MHz region may be due mostly to COOH groups as the contribution of CO groups is negligible except at very high temperatures. Muus showed that the possible cause for the intense absorptions in the lower frequency region (low kHz) may be due to the OH groups in the crystalline portion of the cellulose and that the less-intense absorptions in the high frequency (100 kHz to 100 MHz) region are due to free OH groups in the amorphous portion of the cellulose.

According to Norimoto (1976) the dielectric constant of the crystalline part of cellulose is 3.88 and that of the amorphous part 8.60 (10 kHz, 30°C). Kane (1955) also determined these values for "inaccessible", i.e., crystalline cellulose and "accessible", i.e., amorphous cellulose. Norimoto (1976) further found that the degree of crystallinity of cellulose strongly influences the amount of polarization. Support for this theory is also provided by the work of Ishida et al. (1959) who found from Cole-Cole plots that the magnitude of the relaxation phenomenon increased with increased crystallinity of the cellulose. Venkateswaran (1969) also found similar values for the intrinsic dielectric constant using X-ray diffraction analyses. Verseput (1951) also reported that the dielectric constant of cellulose increases with an increasing degree of crystallinity. Norimoto (1976) concluded that the major contribution to dielectric relaxation in dry cellulose may be associated with the orientation polarization of the methylol dipole in the non-crystalline region.

Lignin is a random, three-dimensional high-molecular-weight polymer composite of phenyl propane units containing OH and OCH_3 polar groups. Both lignin and hemicellulose are associated with CO and COOH polar groups. Hardwoods typically contain about 75% holocellulose with about 25% lignin. Norimoto found that, based on the behavior of p-coumaryl alcohol (a substance that has similar dielectric behavior to milled wood lignin (MWL)), the dielectric absorption may be closely associated with hydroxyl groups, i.e., alcohol and phenolic hydroxyl groups instead of the carbonyl groups. This is because no significant change in the absorption takes place by reducing the carbonyl group of MWL by sodium borohydride. He further found that two different types of dielectric absorption occurred, one at a higher frequency (100 kHz to 1 MHz) and the other at a low frequency (3 kHz to 5 kHz). It was theorized that the high frequency relaxation process may be attributable to the reorientation of the methylol group in MWL. The relaxation process in the low frequency region may be attributed to water absorbed to phenolic hydroxyl groups. The hydrogen bonds between the water molecule and phenolic hydroxyl group is greater (13.9 kcal/mole) than that between a water molecule and an alcohol hydroxyl group (8.7 kcal/mole).

Nanassy (1972) cites the work of Calkins (1950) and Muus (1953) who found that the contributions of non-cellulosic components (i.e., lignin and hemicellulose) contributed significantly to dielectric loss at low frequencies (kHz region). Norimoto (1976) points out that hemicellulose contains mannose and exhibits dielectric dispersion at higher frequencies; however, hemicellulose containing xylose did not show dispersion at higher frequencies. From this he concluded that the relaxation process that occurs in both cellulose and mannan may be associated with the methylol group.

Vermaas (1973) found that resin content had minimal influence on dielectric parameters. Beldi (1968), Kroner and Pungs (1949, 1952), and Torgovnikov (1990) investigated the dielectric behavior of cell-wall substance, glucose, cellulose, lignin, and resin. Evidently glucose, cellulose, and cell-wall material all exhibit the same dielectric loss peak in the frequency range of about 10 MHz, most probably related to the presence of glucose residues. As expected, however, the magnitude of the absorption peak of glucose is more intense but shows less dispersion. Resin, on the other hand had a low dielectric constant and contributed the least amount of polarization. It thus appears that extractives only play a minor role.

2.5 Dielectric Measurement Methods

Procedures and recommendations for determining dielectric properties of materials are specified by standards committees such as ASTM (ASTM D150-74, 1986, for insulating materials). Although these provide a minimal set of guidelines, often each dielectric material is unique and may require further characterization. Several sources, for example, CRC (Weast et al., 1989), list dielectric parameters of dielectric materials including gases, liquids and solids. When a material exhibits significant dielectric dispersion or is subject to temperature effects, it becomes essential to list dielectric parameters at various frequencies and temperatures for future reference purposes.

Instrumental methods for determination of the dielectric properties of wood may be divided into roughly three main categories: bridge devices, resonant devices, and network impedance analyzers. These instruments determine the complex dielectric constant or its components (dielectric constant and loss factor) by indirect means. Both frequency-domain and time-domain principles are used in such instrumentation. A device operates in the frequency domain when the method relies on measurements at one or more distinct electromagnetic frequencies. Time domain methodology on the other hand, applies an electromagnetic perturbation to the material under test and analyzes the resultant electric behavior of the material as a series of events over a very brief moment in time. As indicated by Anagnostopoulou-Konsta et al. (1989), some relaxation phenomena of wood have such short periods that data acquisition rates in the order of 10^6 to 10^9 samples per second (SPS) are required. The transformation between the time and the frequency domains are accomplished using Fourier and inverse Fourier transforms respectively. Time domain techniques have been used to make great advances in Fourier Transform infrared (FTIR) analysis, but have not yet been applied to wood dielectrics.

Frequency domain dielectric measurement methods and procedures have been the subject of many papers and books. Some references that have proved useful in this study were Anon. (1987, 1989), Anderson (1964), Bierwirth and Hoyler (1943), Brettel et al. (1988), Hartshorn and Ward (1936), Hartshorn (1942), von Hippel (1954, 1961), Hojendal (1946), Itchijo (1953), Iinuma (1930), and Peterson (1951).

The majority of wood dielectric research has been carried out using bridge and resonant techniques. For his research on wood, Venkateswaran (1960) describes the conventional bridge and Q-measurement devices that operate in the frequency range from DC to 10^8 Hz. In the frequency range 1 Hz to 10^7 Hz, the capacitance and dissipation factor of a dielectric specimen is obtained by a null method, involving some type of capacitance bridge. For measurements in the frequency range 10^2 Hz to 10^4 Hz, Venkateswaran used a type 716-C Schering bridge manufactured by the General Radio Company, Massachusetts. This type of bridge, however, is not suitable for application at frequencies above 5 MHz as the errors due to stray capacitance and inductance effects become excessive. For measurements in the frequency range 10^5 Hz to 10^8 Hz, he used a type T.F. 329-G, "Circuit Magnification Meter" manufactured by Marconi Instruments Ltd., England.

For the measurement of dielectric constant and loss tangent at frequencies of 1 MHz or greater, James (1975) used a Boonton model 160-A Q-meter. He did experience difficulties when using this instrument on moist specimens and suggested using an alternate voltmeter for those cases. For frequencies of 100 kHz or less, data were taken using the approximate equivalent of a General Radio model 716-C capacitance bridge with a Hewlett-Packard model 200CD oscillator and General Radio 1232-A tuned null detector. Peterson (1951) also mentions this problem of working with high moisture content samples. Ichijo (1953) has shown that the measurement of dielectric parameters of moist wood is possible by using a resonant device where such extreme loading effects could be isolated from the main resonance circuit. He subsequently devised a circuit based on a double resonant approach to address these problems.

In the high frequency range (10 MHz to 30 MHz), special considerations become necessary as errors associated with stray capacitance and inductances become large. Hojendahl (1946) used a resonance technique developed by Iinuma (1930, 1931). This technique was based on a vacuum-tube oscillator with the sample holder forming part of a parallel capacitor-inductor (LC) tank circuit. The novelty of this method was that it required neither radio-frequency measuring instruments and standard, nor special sources of radio-frequency currents. Results obtained by this method were within 2.5% of those obtained using conventional bridge measurements.

Network impedance analyzers are a modern approach that allows for the rapid determination of dielectric parameters such as dielectric constant, loss factor and Cole-Cole plots. The application of such instrumentation for characterizing wood and wood-based materials, has been suggested by Brettel et al. (1988). This kind of approach is also described in greater detail by MacDonald (1987) and includes other swept-frequency devices such as the frequency response analyzer (FRA). Special probes, such as the HP 85070A/B dielectric probe manufactured by the Hewlett-Packard company, are designed for these nondestructive dielectric measurements. This type of probe is basically an open-ended coaxial transmission line which when pressed against the material under test creates a short circuit in the transmission line. At the probe-material interface, a weak fringe field is emitted that penetrates the material under test. Applying network analysis and transmission line theory, the unknown material's impedance is found and the corresponding dielectric parameters subsequently found by indirect calculation.

Unfortunately the use of a transmission-line probe is a tradeoff between convenience and accuracy. The HP 85070A, for example, is usable in the 200 MHz to 20 GHz frequency range with typical accuracy of 5%. The upper limit is often determined by network analyzer performance. Uncertainties at the lower frequency side are determined mainly by the coaxial transmission line's characteristic as well as the nature of the emitted fringe field at the sensor-material interface. Therefore the low frequency readings may only be within 20% of the actual value.

Inaccuracies at these frequencies are most noticeable for materials with dielectric constants below 5. To extend the lower frequency range of this type of probe, Stuchly et al. (1986) improved the sensitivity of the coaxial probe to operate the device in the 10 kHz to 100 MHz range. They found that the experimental error for fringe-field measurements for the modified sensor was in the order of 32% of the theoretically expected; that is an improvement over the standard probe's accuracy. In a subsequent paper, Karunanayake et al. (1988) proposed further alternatives for increasing fringe capacitance for the coaxial probe that increased measurement accuracy to within approximately 12% of the actual value. These values of accuracy were determined using liquids with known dielectric properties.

Pyper et al. (1985) have shown that the coaxial probe and network analyzer approach, when used with a "measurement system" model, may produce dielectric measurement accuracy in the order of 1% - 2% accuracy in the microwave region. Their method is an extension of the Hewlett Packard Accuracy Improved Method (AIM) and involves the determination of noise characteristics and other anomalies with respect to a known reference material.

2.6 Accuracy and Repeatability of Dielectric Measurement Methods

In the above references to apparatus for the measurement of the loss factor of wood, most authors only specified the type of instrumentation used, its manufacturer, and in some instances alternate procedures for the measurement of loss factor. Sometimes the working principle of the instruments is derived from first principles (Beldi et al. 1968, Peterson, 1951, Skaar, 1948., Venkateswaran, 1960).

Other authors for example, Nanassy (1970), referred the reader to the work of Von Hippel (1954) or Hartshorn and Ward (1936). Although it must be assumed that measurements were carried out according to design specifications or manufacturers' instructions, there still remain two major issues: (1) the design of the sample holder and its edge effects, and (2) noise and stability of the RF signal source. Addressing these issues, Skaar (1946) discussed the effects of stray (fringe) capacitance and suggested the use of a double sandwich-type sample holder such as described by Brown et al. (1947). The physical dimensions of the specimens were also chosen such that sufficient overlap of wood material was present in the fringe fields. However, not all fringe effects could be explained. ASTM specification D150 (1986) further recommends a guarded sensor design. Unfortunately, this design involves some nonlinearities that are dependant on the unknown magnitude of unknown dielectric under test that complicate calculations for capacitance determination.

Accurate measurement of the loss factor for wood is a particularly difficult undertaking due to the extreme range of conductance of wood from its green to its dry state. The dominant effect that moisture content has on dielectric measurements is the main reason most research deals with wood in its dry state or below fiber saturation point. This problem was reported both by Peterson (1960) and James (1975) when dealing with higher moisture content samples; however, neither suggested an acceptable alternate solution.

There are sparse references to the accuracy of dielectric instruments used on wood. One is by Beldi et al. (1968) who used the Q-measurement method and specified an accuracy of $\pm 10\%$. Bussey (1967) reviewed various methods for the measurement of dielectric loss and concluded that it is possible to obtain a 5% - 10% accuracy for loss tangent.

It would be useful if an instrument used for making dielectric measurements were tested using a standard dielectric material, preferably a "traceable" standard. Unfortunately, there presently is no such "traceable" standard for dielectrics (Mopsik, 1984). However, there are some materials with known properties that may be used for calibration purposes. The main sources of measurement inaccuracy can be attributed to four factors: (1) fringe field effects, (2) experimental errors, (3) the solid-electrode interface effects, and (4) physical and chemical characteristics of the material.

Capacitive electrodes have fringe fields. These fringe fields may be extensive in unguarded systems and lead to measured capacitances greater than expected. The magnitude of capacitance measurement error due to fringe field effects is dependent on several factors such as electrode thickness, electrode separation, dielectric constant and loss factor of the medium and the geometry of the guard electrodes. ASTM D150 (1986) provides a formula for the calculation of the expected error due to fringe fields in guarded electrodes.

Mopsik (1984) assessed a number of experimental errors such as tolerance in measurements for electrode area, specimen thickness, and accuracy of the instrumentation for measurement of voltage, current, frequency, and phase. The magnitudes of these errors are often directly influenced by the dielectric properties of the medium. For instance, results obtained using a network analyzer will be reasonably accurate when working with dielectrics with a high loss factor (within

1%); however, when working with low loss dielectrics the expected accuracy is often not better than 1%. Resonant techniques may be subject to errors when dealing with low Q dielectric materials such as moist wood.

Errors may be introduced by the solid-electrode interface. Air gaps are often introduced due to rough specimen surfaces, misaligned electrodes, or inadequate contact pressure. When air gaps are present at the interface between the electrode and the specimen, lower values for dielectric measurements may result. This is because air gaps effectively introduce additional series capacitance with the capacitive electrode. Since air is a low loss dielectric, the effective capacitance of the system is greatly reduced.

Material that consists of a mixture of components shows complex dielectric behavior with several regions of intense absorption. Tinga (1969) studied the dielectric behavior of wood modeled as a cellulose-air-water mixture and proposed several models based on material composed of multiphased inclusions. Clearly, material density, which is the ratio of the mixture of the different components making up the material, will play an important role.

2.7 Historical Overview of Dielectric-based Nondestructive Evaluation Techniques

According to Hojendahl (1946), the first systematic investigation of the dielectric constant of wood is due to Starke, who in 1897 discovered the remarkable dependency of the dielectric constant on the direction of the fibers and showed that the dielectric constant increases with moisture content. Hojendahl further pointed out the work done by Hoch in 1922 in investigating dielectric loss in wood.

According to Hartley and Schneider (1989), research by Hiruma (1915) and Hasselblatt (1926) found a linear relationship between the logarithm of the electrical resistivity of wood and its moisture content, with resistivity decreasing as moisture content increases. Stamm (1927) experimentally confirmed these findings. Hasselblatt (1926) suggested that this relationship would continue up to the fiber saturation point (FSP), and the resistance would not change appreciably above FSP.

Tiemann (1951) described the Nodon-Bretteneau heating process as applied to wood dating back to 1910. He further mentioned a patent relating to dielectric heating of wood awarded to W.R. Whitney of the General Electric Company in 1929 (See also Kollmann and Cote, 1968). The process of dielectric heating of wood glue bonds was covered by a U.S. patent in 1937 awarded to E.C. Pitman of the Du Pont Corporation. Some German patents relating to the application of RF heating to wood drying were awarded to Jubitz of the Siemens Company in 1936, and another to a German researcher, Roggendorf, that included the drying of wood using RF energy.

Tiemann also mentions the results of research on RF drying of hardwood species in the Soviet Union by S. Abramenko and N.S. Seliugin dating to about 1933. These Soviet researchers showed that up to 300 percent decreases in drying times was possible. These claims were consistent with results done on smaller test samples by Tiemann in 1936.

3. EXPERIMENTAL PLAN OF STUDY

Overall reseach objectives and typical test conditions, i.e., moisture content, RF excitation, and room conditions are presented in this section. In addition, an overview of the experimental procedure, wood sample set, moisture conditioning procedure, and data analysis method is also described.

3.1 Overall Research Objective

The objective for this research was to investigate the behavior of dielectric properties of commonly-found wood surface features under different test conditions. Stringent accuracy and repeatability specifications for instrumentation led to the development of a new device called a dielectric spectrometer. Subsequent experimental work then explored various wood features under tightly-controlled conditions. Experimental results from this study were intended to fill the void in the knowledge that exists about the dielectric properties of wood in practice.

3.2 Scope

The dielectric constants and loss tangents of various common wood features were determined at several frequencies in the high frequency (HF) RF range at a variety of moisture contents typically found in practice. All tests were performed in a controlled-environment room maintained at a nominal ambient temperature of 72°F (22.2°C) and 50 percent relative humidity. This temperature was chosen because the literature showed significant temperature effects do not occur until approximately 45°C, which is above those typically found in optical scanning applications.

In addition, the influences of important physical properties of wood such as specific gravity and the number of growth rings per inch were included in this investigation. These physical properties were taken from clear wood portions in the proximity of the wood features of interest. The relationships between the relative physical dimensions of these features and the corresponding dielectric properties were also investigated.

The sheer volume of experimental readings associated with the planned experimental work, necessitated that this part of the research be structured into two parts: The first part of the experimental research was intended to gain insight into how well the instrumentation was performing and to narrow the scope of the experiment to practical limits. The second part of the experimental research was to evaluate statistically a wider range of wood features over a range of typical moisture and excitation frequency conditions.

3.3 Wood Features Investigated

The dielectric spectrometer's active sensing area was a disk with a diameter of 0.75 inches. In general, the wood features investigated are commonly found on Douglas-fir wood surfaces and include the following:

1. Loose knots (large, medium, small),
2. Tight knots (large, medium, small),
3. Holes (small, medium, large),
4. Pitch pocket (small and large),
5. Pitch streak (small and large),
6. Blue stain (heavy and light),
7. Clear wood (heartwood and sapwood).

During the preliminary experiment, a subset consisting of the following wood features was investigated:

1. Tight knots (large, medium, and small),
2. Blue stain
3. Clear wood (heart and sap)

For the extended experiment, the full sample set as listed above, except for the heart/sap subgroup for clearwood, were investigated:

1. Loose knots (large, medium, small),
2. Tight knots (large, medium, small),
3. Holes (small, medium, large),
4. Pitch pocket (small and large),
5. Pitch streak (small and large),
6. Blue stain (heavy and light),
7. Clearwood.

Small in this context refers to features with dimensions smaller than the 0.75 inch sensor, medium means the feature is approximately 0.75 inch, and large is for features greater in size than the sensor. Heavy and light blue stain classifications follow WWPA (1988) grading rules. Samples were cut to uniform thickness and parallel surfaces using a fine-toothed circular saw and a special jig. Smooth surfaces were produced using this method that required no further sanding or planing.

3.4 Frequencies Used for Tests

Using the information presented by Nanassy (1970), test frequencies of 1.4, 4, 10, 20, and 49 MHz were chosen for this research. Those frequencies corresponded to the start, middle portion, and maximum portion of the high frequency dipolar absorption region, respectively. The dielectric spectrometer was provided with a series of plug-in modules corresponding to each frequency.

The full set of frequencies (1.4, 4, 10, 20, and 49 MHz) was used in the preliminary experiment, while only a subset of frequencies (1.4, 10, and 20 MHz) was used during the extended experiment. These selected frequencies for the extended experiment was determined from results of the preliminary experiment.

3.5 Moisture Content Range

The moisture contents chosen corresponded to levels commonly found in lumber processing. Such a moisture content range allowed for the study of localized moisture absorption effects associated with wood features. The moisture content levels were achieved using saturated salt solutions in an attempt to accurately achieve known moisture levels. Five levels of equilibrium moisture content (EMC), 25%, 10%, 6.6%, and 0% (oven-dry) were tested. For the 6.6% EMC level, Magnesium Chloride was used, at 10% EMC, Manganese Chloride, and at 25% EMC, Sodium Sulphate. The 0% state was achieved by oven-drying (ASTM D2016-73). At each of these moisture levels, several identical desiccators were prepared with forced-air circulated and saturated salt solutions. Actual sample moisture content was determined gravimetrically at the time that the dielectric properties were measured. This was necessary because various categories of samples reacted somewhat differently during conditioning and stabilized at moisture content levels slightly different than the target moisture content level.

The sample selection process somehow complicated how moisture conditioning was performed. Samples were obtained from kiln-dried boards, each selected to contain only the particular feature of interest. Moisture conditioning thus started from samples that already had gone though moisture desorption. However, the experimental plan called for the lowest non-ovendry moisture level to be below the average environmental level. Therefore, another desorption step, was required before the samples went through several sorption stages to the higher target moisture levels. It was expected that a certain amount of moisture hysteresis would be evident in the experiment, but it would be of lesser significance than the effects of the moisture steps. It should also be noted that the highest possible equilibrium moisture level for a sorption step for kiln-dried samples is approximately 20%, which will be below the fiber saturation point.

During the preliminary experiment, the full set of nominal moisture contents was used for measurements (0%, 6.6%, 10%, and 25%). The preliminary experiment showed that the zero percent moisture content was not practical due to sample warping even when samples were restrained. For this reason only three moisture levels were used (6.6%, 10%, and 25%) in the extended experiment.

3.6 Statistical Analysis

The SAS® statistical package was used to analyze the experimental data using the general linear model (GLM) analysis of variance (ANOVA). Because of the nature of the experimental design for the preliminary and extended experiments, each feature group is considered as its own control in a repeated measures design. The general linear model procedure is required when an unbalanced (an unequal number of observations in the cells) design is analyzed. For the preliminary experiment, this was necessary as the number of blue stain samples was different from the number of clear wood samples. Missing values (due to warping) also needed to be accommodated. In the case of the extended experiment, several of the feature groups categorized subfeatures differently. The pitch pocket group for instance considered small and large pockets, while the knots considered large, medium, and small categories.

Results of this ANOVA should be considered carefully as several assumptions are made: 1) that the factors are fixed, 2) that the variability between feature groups is similar. For practical reasons, actual sample moisture content, for example, often differs from the nominal values. Comparisons for the means of the dielectric constant in these cases may prove inappropriate. This is because moisture has such a strong influence on dielectric constant and slight differences in the actual moisture content between feature groups may translate in different interpretations.

4. INSTRUMENTATION

As pointed out in the literature review, several possible instrumental methods for measurement of the dielectric constant and loss factor of wood were available for consideration. Because the frequency range for this study was limited to 1.4 MHz to 49 MHz, particular interest was paid to aspects of accuracy, resolution, stability, physical shape and size requirements for the test specimens, and to a lesser degree, cost and ease of use.

4.1 General Considerations

Wood specimens to be tested consisted of smooth strips of wood approximately three inches wide and six inches long with uniform thicknesses that were in the range of 0.05 to 0.1 inch. Considering the nature of the properties of wood to be studied, it was decided that the sensor would be circular with an active sensor diameter not larger than 0.75 inch. Such a sensor would integrate dielectric properties over the area of the sensor in contact with wood.

The theoretically-calculated capacitance for a 0.75 inch diameter, 0.1 inch air gap parallel-plate capacitor is 0.994 pF. If the dielectric between the capacitor electrodes is dry wood (dielectric constant approximately 2.2), the capacitance will be approximately 2.19 pF. For a dielectric consisting of green wood (dielectric constant of approximately 35), the capacitance would be approximately 34.77 pF. If it is anticipated that the smallest wood feature of interest introduces a variation of

1% in dielectric properties, this translates to a resolution requirement of at least 0.022 pF and 0.35 pF for dry wood and green wood respectively.

4.2 Hardware Considerations

Considering the resolution requirement discussed in Section 4.1, a guarded electrode specimen holder was deemed to be essential to minimize pickup of extraneous signals. ASTM D150-74 (1986) provided useful guidelines for the design of the guarded electrode used in this research. Such an electrode, however, may be used with several different measurement techniques, whose appropriateness needed further consideration. These techniques included network analysis using an RF sweep generator/vector voltmeter and the more classical approach based on Q-measurement of resonant circuits.

Network analysis offers attractive possibilities such as ease of use and a wide operating range. However, as shown in the literature review, there are disadvantages when attempting to use a single electrode system covering an extended frequency range. For these reasons, the classical method based on resonant circuits and in particular, the design by Ichijo (1953) was chosen for its ability to measure materials with high loss factors.

The working principle is based on the substitution method, which involves taking an impedance measurement of the unknown specimen, then finding the equivalent matching impedance using calibrated dials. Some of the labor intensive data collection and calculations of dielectric constant and loss factor were simplified using an automated data acquisition system.

4.3 Practical Considerations

The original design frequency for Ichijo's device was specified for a maximum of 2 MHz, with possible use up to approximately 10 MHz. As in most devices of this type, the upper frequency is limited mainly by stray reactance introduced by circuit components as well as proximity effects between components. Sensor geometry and construction practice also play important parts in the usefulness of the device at higher frequencies.

Although the highest usable frequency may be extended by careful construction practice, a practical upper limit is reached somewhere between 30 MHz and 100 MHz. The device used in this study produced very reasonable results at 20 MHz and useful results at 49 MHz. This was achieved by observing proper RF construction practices and component placement. Teflon® and ceramic insulators were used liberally in active RF circuits.

Electronic determination of total circuit capacitance is made possible using shaft encoders fitted to the rotor shafts of tuning capacitors. Angular position of the rotors of these capacitors, and thus circuit capacitance, is converted to analog output voltages. These analog voltages are digitized using a personal computer (PC) based data acquisition subsystem. This automation greatly simplifies the tedious task of selecting resonance peaks and the subsequent calculation of dielectric constant and loss factor.

4.4 Stability

Both long-term and short-term stability is necessary to ensure repeatability and reproducibility of experiments. Long-term stability is essential where a multitude of readings need to be taken over time. Short-term stability is essential to reduce variability between replications of readings on the same measurement point. Because of the small magnitude of dielectric differences of some wood features of interest, any improvement in the stability of the instrumentation is worthwhile. The RF signal generator uses several discrete quartz crystal oscillators at 1.4, 4, 10, 20, 30, and 49 MHz to provide frequency-stabilized signal sources. These signals are extensively buffered to minimize loading effects, thus enhancing stability of the output of the excitation source.

Repeatability of results is also dependent on the mechanical stability of the measurement electrode. Good mechanical repeatability is achieved by mounting the electrodes on a precision linear transport mechanism. The transport mechanism chosen is intended for usage on an optical bench and is outfitted with a 1/1000 inch micrometer drive. Not only does this transport mechanism precisely control electrode separation, it also enhances rigidity and parallelism of the electrodes. In addition, specimen thickness measurements to within 1/1000 inch accuracy may be made with this arrangement.

For a detailed analysis of the working principles of the instrumentation, please see Appendix 1, "An Analysis of the Double Resonant Technique for the Measurement of Dielectric Properties of Wood." Calibration and repeatability results for the instrument are described in Appendix 2 "Dielectric Spectrometer Calibration and Repeatability Evaluation." The conclusions drawn from the Appendices 1 and 2 may be summarized as follows:

1. The derivation of measurement principles in Itchjo's article contains some typographical errors. Since this is particularly important if these formulae are to be implemented, the correct derivation is shown in Appendix 1.

2. For the range of frequencies 1 to 50 MHz, Ichijo's assumptions for simplification are no longer valid as certain capacitive reactances become significantly large.

3. The method of operation devised for this research relies on

   a) a substitution method for the dielectric constant that requires a peak picking algorithm and

   b) a Q-measurement method for loss tangent determination based on a simple ratio determination.

Both these factors are computed during the data collection phase. However, final calculations of the dielectric constant and loss tangent require data from a calibration step to compensate for stray reactances and other errors within the dielectric spectrometer. The calibration data are acquired frequently, typically before a batch of measurements.

5. PRELIMINARY EXPERIMENT

As discussed in Section 3, a preliminary experiment was conducted to serve as a pilot study for the larger, more comprehensive project and was thus designed to test and evaluate several key components and procedures.

5.1 Objective for Preliminary Experiment

The objectives for the preliminary experiment included:

1) Establishment of guidelines for the use of the dielectric spectrometer.

2) Resolution, accuracy, repeatability, and reproducibility of results.

3) Evaluation of the data acquisition software, calibration procedures, and data reduction procedures.

4) Determination of the dielectric spectrometer's capability for detecting the differences, if any, between clear heartwood and sapwood, as well as the presence of blue stain.

5.2 Preliminary Experiment Sample Selection and Preparation

Eight groups, each consisting of three samples, were prepared to investigate five wood features: blue stain, heartwood/sapwood boundary, large-sized tight knots, medium-sized tight knots, and small-sized tight knots. Sample type and designation followed the convention listed in Table 5.1.

Table 5.1. Sample nomenclature for preliminary experiment.

1. Blue stain: Group 1: BS1A - light blue stain - sapwood BS1B - light blue stain - heartwood/sapwood boundary BS1C - all clear - heartwood Group 2: BS2A - light blue stain - sapwood BS2B - light blue stain - heartwood/sapwood boundary BS2C - all clear - heartwood Group 3: BS3A - light blue stain - sapwood BS3B - light blue stain - heartwood/sapwood boundary BS3C - all clear - heartwood
2. Heart/sapwood: Group 4: CLH1 - Clear heartwood CLH2 - Clear heartwood CLH3 - Clear heartwood Group 5: CLS1 - Clear sapwood CLS2 - Clear sapwood CLS3 - Clear sapwood
3. Large tight knots: Group 6: TKL1 $>$ 3/4 inch diameter TKL2 $>$ 3/4 inch diameter TKL3 $>$ 3/4 inch diameter
4. Medium tight knots: Group 7: $1/4 \leq$ TKM1 $<$ 3/4 inch diameter knot $1/4 \leq$ TKM2 $<$ 3/4 inch diameter knot $1/4 \leq$ TKM3 $<$ 3/4 inch diameter knot
5. Small tight knots: Group 8: TKS1 $<$ 1/4 inch diameter knot TKS2 $<$ 1/4 inch diameter knot TKS3 $<$ 1/4 inch diameter knot

In an attempt to limit variation of basic wood properties within each group, all samples within each group were cut from a common block of wood with the samples taken from adjacent wood material. In the case for blue stain that occurs only in sapwood, the samples were taken from near the heartwood/sapwood boundary. In this instance, two blue stain samples came from the sapwood and one sample from the adjacent heartwood. The intention was to investigate differences between clear wood and blue-stained wood.

Each block of wood measured approximately eight inches in length oriented in the longitudinal fiber direction. Sample widths varied from 1.5 inches to three inches and were cut to produce as nearly as possible a tangential face. The thickness of each sample was approximately 0.1 inch. However, this dimension was remeasured each time a dielectric measurement was taken to accommodate thickness swelling or shrinkage.

An estimate of basic wood properties for each block was made by taking a one inch cross-section from each end of the block before the samples were prepared. One cross-section taken from the end of the block was used to determine the number of rings per inch and the wood density (ASTM D2395-83 method B - volume by water immersion). Another cross-section sample was used to determine the initial moisture content (ASTM D2016-74 - oven-dry method).

The resulting basic wood parameters are listed in Table 5.2. Figure 5.1 shows the relationship between specific gravity and the number of growth rings per inch. There appears to be a weak relationship (R^2=0.4615) between specific gravity and the number of growth rings per inch for the particular sample set.

It should be noted that these wood samples represented a range of densities, number of growth rings per inch, and initial moisture contents. Some of these factors were particularly important when considering dimensional stability when the samples were dried from the fiber saturation point to the oven-dry state. Samples cut from old-growth wood that, for example, has a multitude of rings per inch, produces nearly homogeneous flat sawn or quarter-sawn sections. Compared to samples cut from second-growth wood that has a low number of rings per inch, these show distinct regions of higher density (due to summerwood) and lower density (due to springwood) on a cross section. Making tangentially-cut samples from such wood results in surface areas of considerable variation in density as the section is cut almost parallel to these growth rings. The literature (Skaar 1948; Torgovnikov 1990) have shown that wood density affects the dielectric parameters and it is thus expected that these difference in the numbers of growth rings per inch will introduce a certain degree of variability of dielectric parameters of sample surfaces.

Table 5.2. Basic wood properties for the ends cut from the blocks used to produce the preliminary study samples.

Sample group	Initial moisture content (%)	Specific gravity S.G.	Rings per inch
BS1	15.36	0.45	6.01
BS2	20.20	0.51	13.95
BS3	14.35	0.43	12.34
CLH	8.85	0.49	12.38
CLS	8.85	0.49	12.38
TKL	10.23	0.42	4.58
TKM	11.82	0.46	11.00
TKS	11.02	0.46	6.72

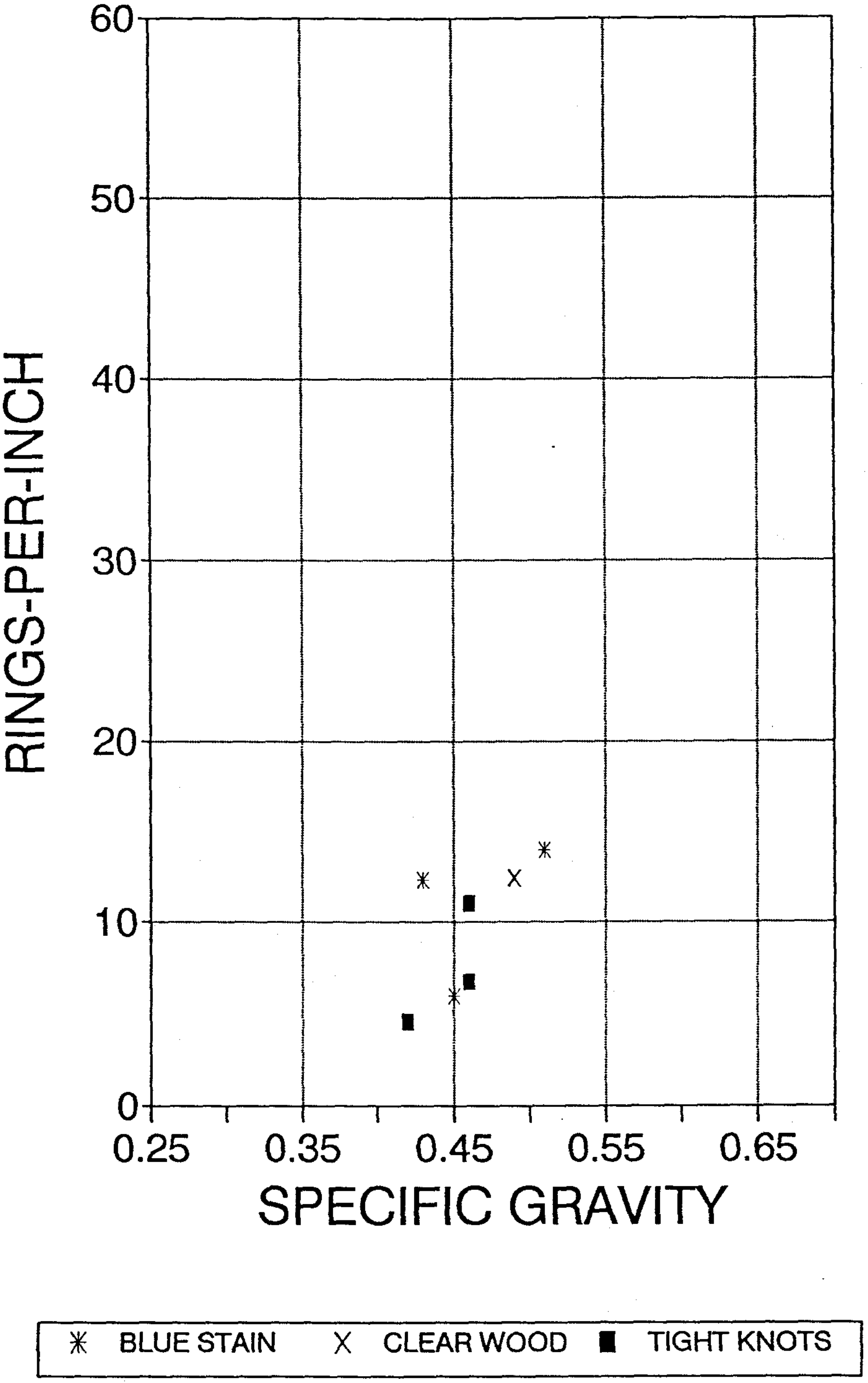

Figure 5.1. Preliminary experiment: Relationship between specific gravity and the number of rings per inch.

5.3 Test Frequencies and Moisture Contents

Four levels of moisture content, 25%, 10%, 6.6%, and oven-dry, were tested. These levels were maintained over forced-air circulated, saturated salt solutions. The experiment was performed at a room temperature of approximately 25°C. Figure 5.2 shows the extent that each sample group attained the target moisture content. A smaller amount of spread in actual sample moisture content is evident at the lower moisture contents (6.6% and 10% MC) than at the highest moisture content level (25% MC). In addition, at the 25% the clearwood samples achieved higher moisture content levels than did the samples of tight knots.

At each moisture content level, five frequencies of 1.4 MHz, 4 MHz, 10 MHz, 20 MHz, and 49 MHz were used. At every frequency and moisture content level, each sample was tested at three locations corresponding to the feature and locations adjacent to the feature of interest. Each location was measured five times.

5.4 Statistical Analysis

The SAS® statistical package was used to analyze the experimental data using the general linear model (GLM) analysis of variance (ANOVA). Because of the nature of the experimental design for the preliminary experiment, each feature group is considered as its own control in a repeated measures design.

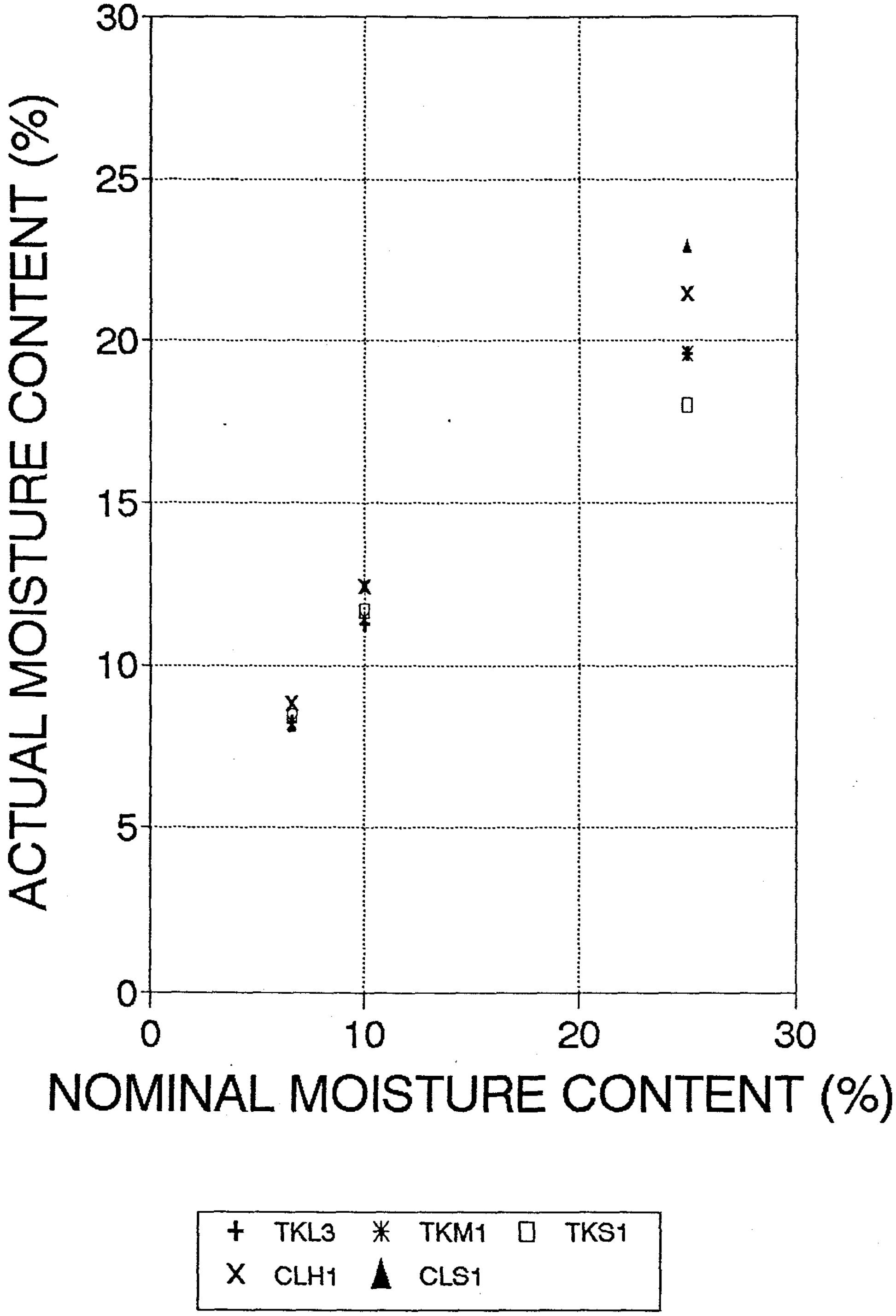

Figure 5.2. Preliminary experiment: Actual and nominal moisture contents for sample set.

Several missing values due to the buckling of some samples at lower moisture levels had to be considered. The buckling caused air gaps that resulted in erroneous readings. The entire blue stain group suffered from this problem because they were sawn from wetter material than the other samples (Table 5.2). Therefore, the entire blue stain group could not be included in any meaningful ANOVA. However, where possible, a limited amount of data are presented in exploratory data plots in raw form. It should also be noted that the experimental design is an unbalanced design with six samples in the clearwood group and nine in each of the other groups. The missing values introduced by the blue stain group reduced the number of feature groups from six to five. These are listed in Table 5.3.

Table 5.3. Allocation of feature groups and their respective number of observations for the preliminary experiment statistical analysis.

Feature Type	Number of Observations
2 - Clear Sapwood	10
3 - Clear Heartwood	14
4 - Tight Knots Large	5
5 - Tight Knots Medium	4
6 - Tight Knots Small	5

The maximum sample size in Table 5.4 (Section 5.5.4) is 15 (3 sample replications by 5 measurement replications). A reduced number of observations are an indication of missing values due to sample warping. As expected, results from the ANOVA tests for dielectric constant and loss tangent showed that feature group, moisture content and frequency, as well as their interactions, were all significant.

This suggested that specific differences between features and groups of features do exist. Those differences were then further investigated on an individual basis.

To aid the process of finding feature groups that had statistically significant differences, the sample means for each feature was plotted with dielectric constant or loss tangent as the dependant variable. A family of curves by frequency was thus produced. To summarize this series of graphs, one graph from each of the feature groups from the SAS linear models were plotted on Figure 5.3 for dielectric constant and on Figure 5.4 for loss tangent comparative purposes. Closer inspection of Figures 5.3 and 5.4 shows the existence of three possible feature groups:

1. Clearwood - combined heart and sapwood.
2. Large and Medium tight knots.
3. Small tight knots.

These observations have been tested on an individual basis and confirmed by their statistical significance. A complete set of graphs showing the effect of moisture content on dielectric constant and loss tangent for different frequencies is shown in detail in Appendix 3: "Preliminary Experiment: Relationship Between Moisture Content and Frequency for Wood Features," Figures A.3.1 to A.3.10. Similarly, a family of graphs plotting dielectric constant and loss tangent as a function of frequency and moisture content is presented in Figures A.3.11 to A.3.30. To summarize the graphs from Appendix 3, Figures 5.5 and 5.6 are taken from Appendix 3, Figures A.3.2: "Effect of Moisture Content on Dielectric Constant for Clear Sapwood at Various Frequencies" and Figure A.3.7: "Effect of Moisture

Content on Loss Tangent for Clear Sapwood at Various Frequencies" respectively. Figures 5.7, 5.8, and 5.9 are taken from Appendix 3, Figure A.3.19: "Dielectric Constant Versus Loss Tangent at 0% MC and 10 MHz," Figure A.3.21: "Dielectric Constant Versus Loss Tangent at 10% MC and 10 MHz," and Figure A.3.13: "Dielectric Constant Versus Loss Tangent at 10% MC and 1.4 MHz."

5.5 Results and Conclusions from Preliminary Experiment

As expected from the literature (Skaar 1948; Torgovnikov 1990; Trapp and Pungs 1956), the results from the preliminary experiment showed that moisture content has a strong affect on dielectric constant and loss tangent. However, they are manifested differently. Dielectric constant, for example is affected to a lesser degree by frequency than loss tangent. Loss tangent results show a complex interaction between moisture and frequency, particularly in the range of 8% to 15% MC approximately.

There are many literature references that deal specifically with the theoretical aspects of the dielectric behavior of wood for predicting the dielectric behavior of wood in the HF region (Venkateswaran 1960, Yavorsky 1951, Nanassy 1970, Skaar 1948). One plausible theory by Venkateswaran (1960) hypothesized that if wood behaved according to the classical Debye theory with a single relaxation mechanism, then conductivity would level off at very high frequencies. Since dielectric loss is related to the product between conductivity and permittivity, this would explain the classical narrow-peaked distribution for the loss factor. This peak of intense dielectric loss corresponds to the single relaxation period. Many polymeric materials including wood, however, are heterogeneous in nature and consist of several different polar groups each with their own relaxation characteristics. The dielectric response of such a material then reflects a distribution of relaxation times. The peak in the loss factor subsequently has a lower magnitude and further is dispersed over a wider range of frequencies. This deviation from the classical Debye theory is often called "anomalous" dielectric dispersion. Thus for the dipolar region, i.e., the region above 100 kHz and extending to the low VHF region (below 300 MHz), the dielectric constant is expected to decrease while the dielectric loss is expected first to increase and then decrease at low VHF frequencies. This dielectric behavior in the HF region has been confirmed for wood by several researchers such as Trapp and Pungs (1956a, 1956b), Yavorsky (1951), Torgovnikov (1990), Tsutsumi and Watanabe (1965), Kollmann and Cote (1968), and Nanassy (1970).

It is unfortunate, however, that a significant portion of important literature on wood dielectrics deals only with the region below the HF region (Norimoto and Yamada 1969; Norimoto 1970, 1971, 1976; Norimoto et al. 1978; Norimoto and Zhao 1993) or otherwise deals with temperature or/and moisture effects at frequencies below the HF region (Tsutsumi and Watanabe 1965; Tsutsumi 1966, 1967). Therefore, no further insight or comparative data are provided for use in this experiment. There is consensus in the literature that the behavior of the dielectric constant for clear wood is relatively uncomplicated, being affected by species, density, moisture content, and temperature (Skaar 1972, James 1975). Dielectric loss, however, is much more variable, perhaps reflecting complex interactions between the chemical constituents of wood, temperature and moisture. Examples of such variability are shown by Yavorsky (1951), Beldi et al. (1968), and Trapp and Pungs (1956).

In certain instances this variability of dielectric loss appears to lead to contradictory results. James (1975) and Beldi et al. (1968) for example, do not show any significant loss factor peak. In contrast, Kollmann and Cote (1968), Trapp and Pungs (1956a, 1956b) and Torgovnikov (1990) report a distinct loss factor peak between 10 MHz and 50 MHz. Nanassy (1970) also shows the existence of a weak loss factor peak even at low temperatures and in the oven-dry state. The loss factor peak is temperature dependent (Nanassy 1970) and moisture dependent (Trapp and Pungs 1956). Further uncertainties regarding the interpretation of dielectric loss are found in Kollmann and Cote (1968), where it is stated that there is a weak correlation between power factor and wood density, whereas Torgovnikov (1990) implies a much stronger correlation between loss tangent and wood density.

5.5.1 Effect of moisture content

The effect of moisture content is evident from Figures 5.7 and 5.8 where the dielectric constant and loss tangent are related to moisture content at the same frequency. An increase in moisture content spreads the ranges of both dielectric constant and loss tangent. For example, Figure 5.7 shows that at 10 MHz, the range in dielectric constant for all features at 0% MC is approximately from 2.0 to 3.0. For 10% moisture content, Figure 5.8 shows the range in dielectric constant from approximately 2.5 to 5.0. This increase due to moisture content is nearly linear for most wood features as shown in the example plot, Figures 5.5. Using this comparison for the loss tangent, Figure 5.7 shows that the range in loss tangent at 0% MC is from approximately 0.03 to 0.06, while at 10% MC this range expands to 0.06 to 0.15. The increase in loss tangent, however does not show the same degree of linearity as shown in Figures 5.6, where the shapes of the relationships are distinctly non-linear.

5.5.2 Effect of frequency

The effect of frequency content is evident from Figures 5.8 and 5.9 where the dielectric constant and loss tangent at 10% MC are shown for 10 MHz and 1.4 MHz. The effect of frequency is a changing of the spread of the ranges of both the dielectric constant and loss tangent. According to the literature, wood typically shows an anomalous dispersion with a region of intense absorption in the HF frequency range. This corresponds to a systematic decrease in the dielectric constant and a peak in loss factor. An indication of this systematic reduction of dielectric constant is observed in Figures 5.8 and 5.9 where the dielectric constant remained unchanged or perhaps underwent a slight reduction when the frequency was increased from 1.4 MHz (Figure 5.9) to 10 MHz (Figure 5.8). The corresponding increase in loss tangent is evident for the 10 MHz in Figure 5.8.

It should be noted that using the means of the dielectric constant and loss tangent predicted by the general linear model effectively smooths out the effect of frequency in the model (see Figures 5.3 and 5.4). This is a result of the fact that the model accounts for the contribution of frequency to the total variance as an experimental error rather than a systematic effect. The literature shows the effect of frequency on loss factor to be nonlinear, which may mean the general linear model does not appropriatly account for the effect of frequency. Rather, a second order transformation may be necessary.

5.5.3 General behavior of clearwood

Clear wood samples include the CLH and CLS groups. For the frequency range of 1.4 MHz to 49 MHz, at zero percent moisture content the dielectric constant range is 2.00 to 2.14 (average=2.06). At a moisture content of 6.6%, the dielectric content range is 2.6 to 2.4 (average=2.5). At 10% moisture content, the corresponding range is 3.2 to 2.75 (average=2.98), and at 18% moisture content, the range for dielectric constant is 3.85 to 4.12 (average=3.88). Therefore, the dielectric constant increased by roughly 1.82 from an initial value of 2.00, while the moisture content increased by 18% from an initial value of 0%. This amounts to a ratio for $\delta\epsilon/\delta MC$ of 0.1011. James (1975) reported slightly higher ranges for the dielectric constant of 3.1 to 2.7 (average 2.9) at 5.1% moisture content, and 4.3 to 3.7 (average 4.0) for 12.2% moisture content. This amounts to a ratio for $\delta\epsilon/\delta MC$ of 0.1549. Peterson (1960) reported a dielectric constant of 2.7 at 6.6% moisture content and 3.3 at 10% moisture content. This amounts to a ratio of $\delta\epsilon/\delta MC$ of 0.1764. Peterson's data, however, are for a fixed frequency of 5 MHz.

Figure 5.6 shows the loss tangent for a range of moisture contents and frequencies for clearwood heart sample group CLH. The complex interaction between frequency and moisture is evident when considering that below approximately 15% MC, loss tangent has a maximum at 10 MHz. Above 15% MC, however, loss tangent behavior is different with lower frequencies showing higher loss tangent than higher frequencies. James (1975) reported an increasing loss tangent ranging from 0.055 to 0.12 at 5.1% MC for frequencies in the range 1 MHz to 50 MHz. At 12.2% MC, however, his data showed a decrease from an initial 0.06 to 0.044, then an increase to 0.13 for the frequency range 1 MHz to 50 MHz. Peterson showed no apparent moisture affect on loss tangent between 6.6% and 10%. In this range he reports a value of 0.057 for loss tangent. Trapp and Pungs (1956) showed a peak in loss tangent for spruce of approximately 0.07 occurring for frequencies over 100 MHz.

5.5.4 Differences between heartwood and sapwood

The ability to detect differences between heartwood and sapwood was evaluated using the SAS general linear model ANOVA approach. The results are summarized in Table 5.4. It is evident from Table 5.4, that no distinction between heartwood and sapwood could be made using loss tangent. However, using the dielectric constant, the 49 MHz frequency level allows such distinction to be made at all moisture levels. At 1.4 or 4 MHz the distinction is possible at low moisture levels (0% and 6.6% MC). Thus it does appear that the 49 MHz frequency level may possibly be used to distinguish between heartwood and sapwood.

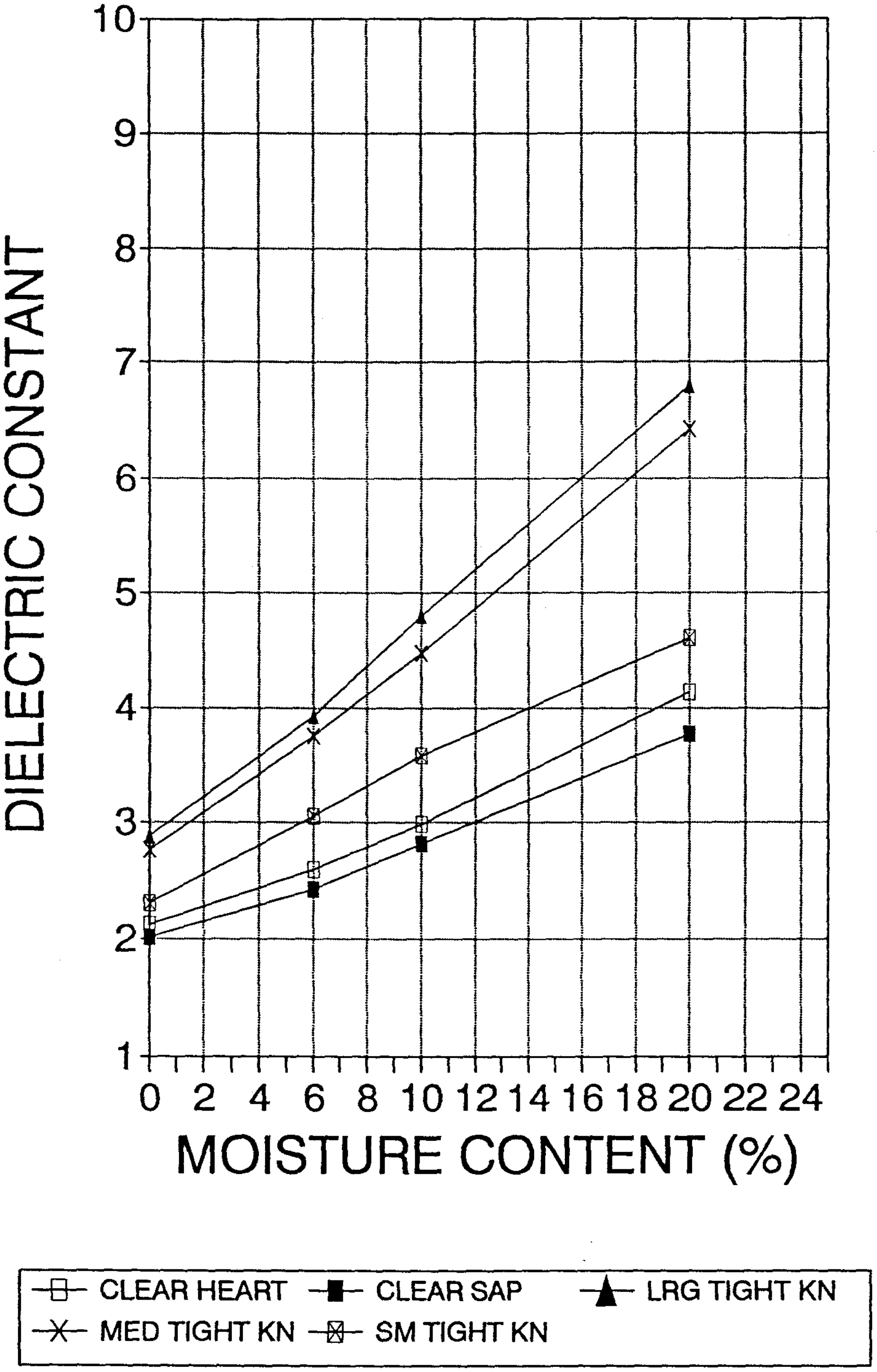

Figure 5.3. Preliminary experiment: The effect of moisture content on the dielectric constant of clear sapwood, clear heartwood, large tight knots, medium tight knots, and small tight knots.

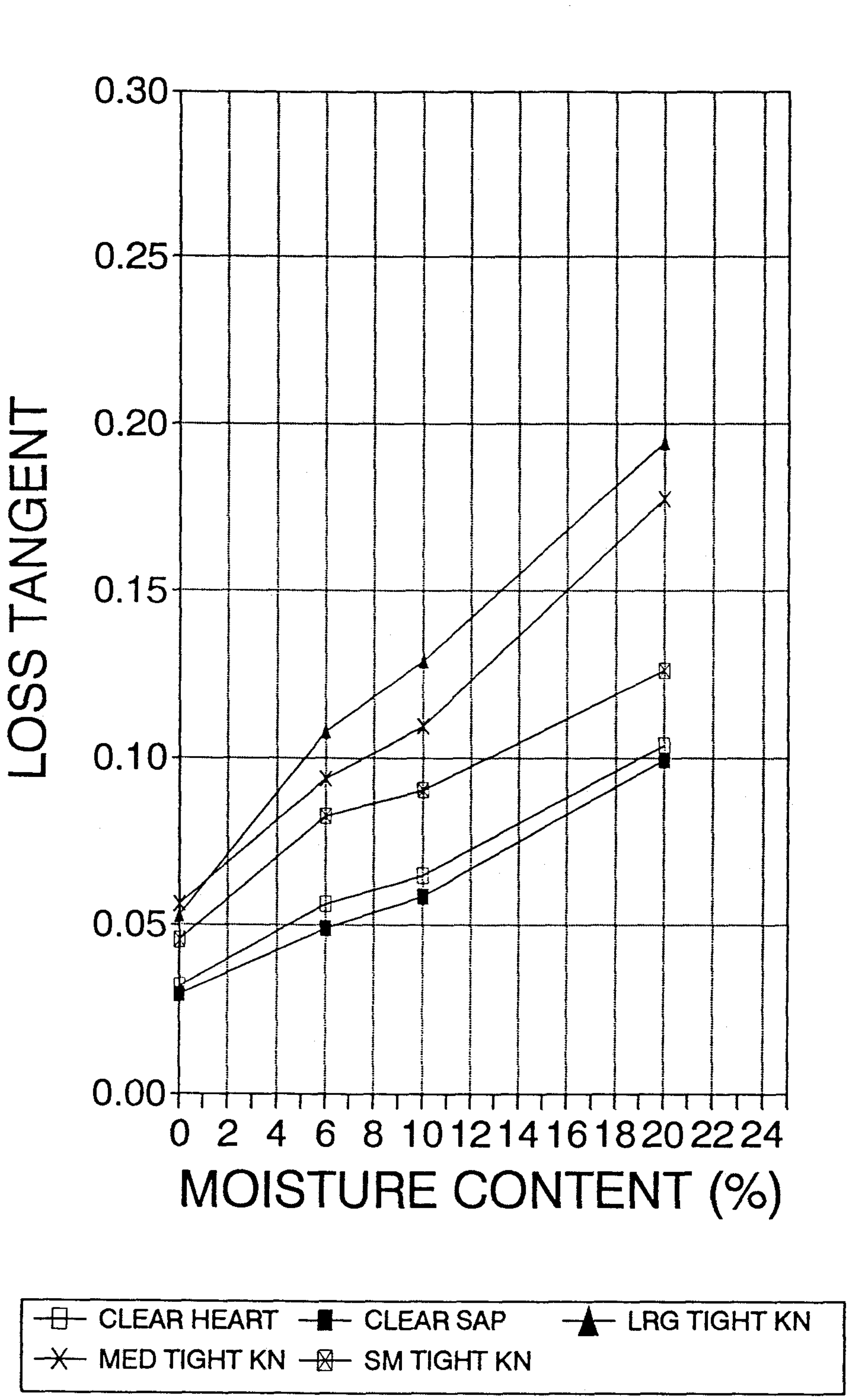

Figure 5.4. Preliminary experiment: The effect of moisture content on the loss tangent of clear sapwood, clear heartwood, large tight knots, medium tight knots, and small tight knots.

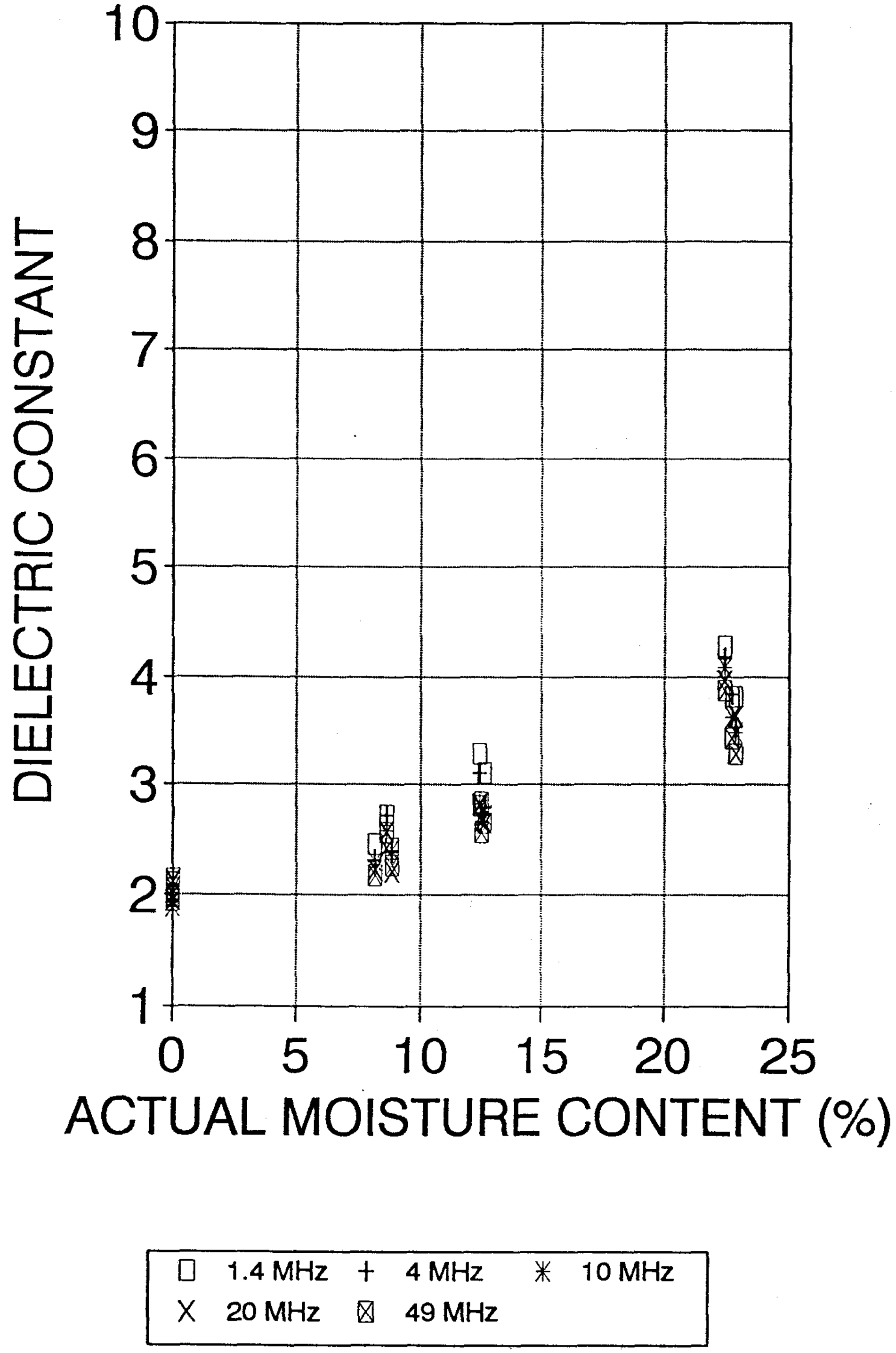

Figure 5.5. Preliminary experiment: The effect of moisture content on the dielectric constant of clear sapwood.

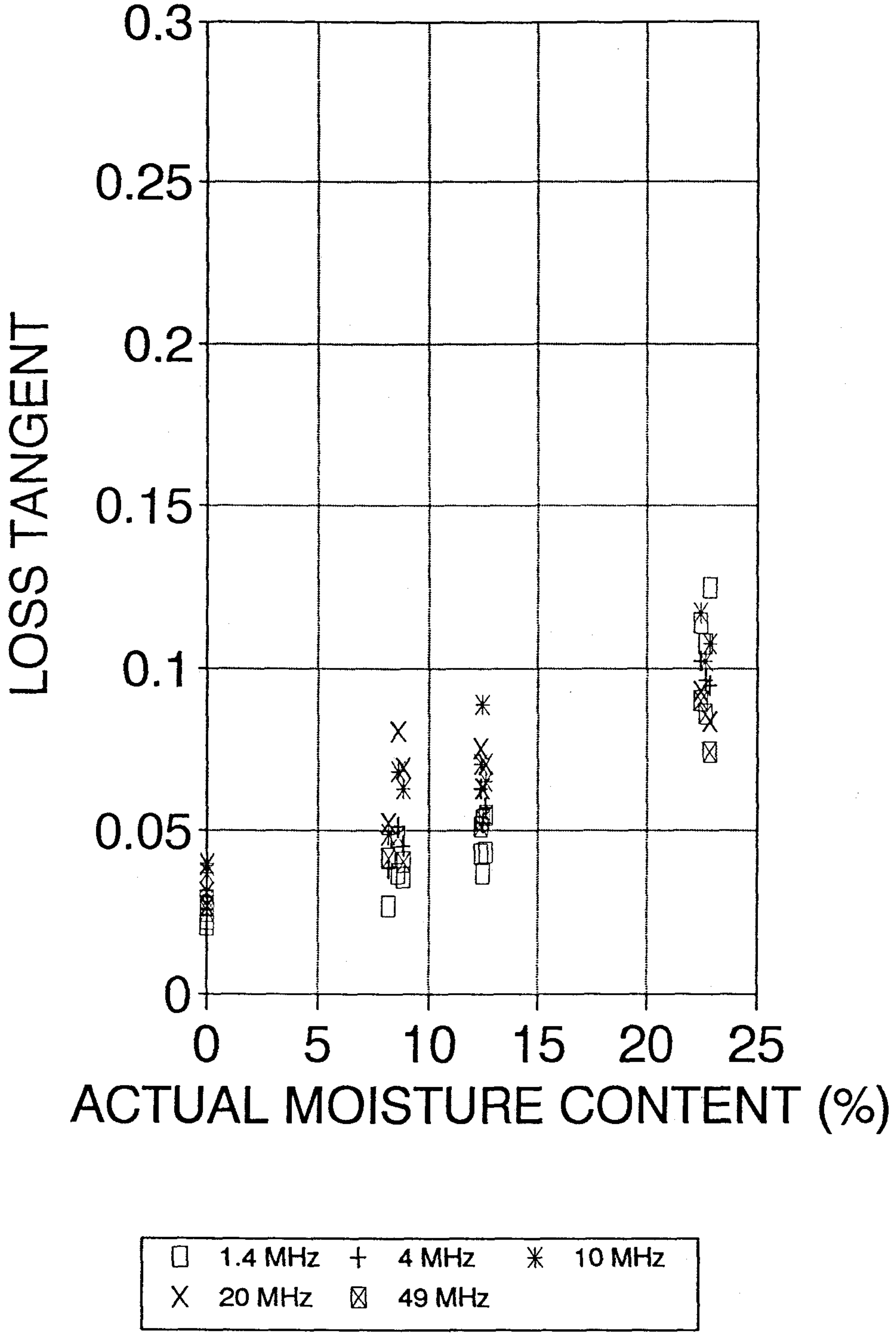

Figure 5.6. Preliminary experiment: The effect of moisture content on the loss tangent of clear sapwood.

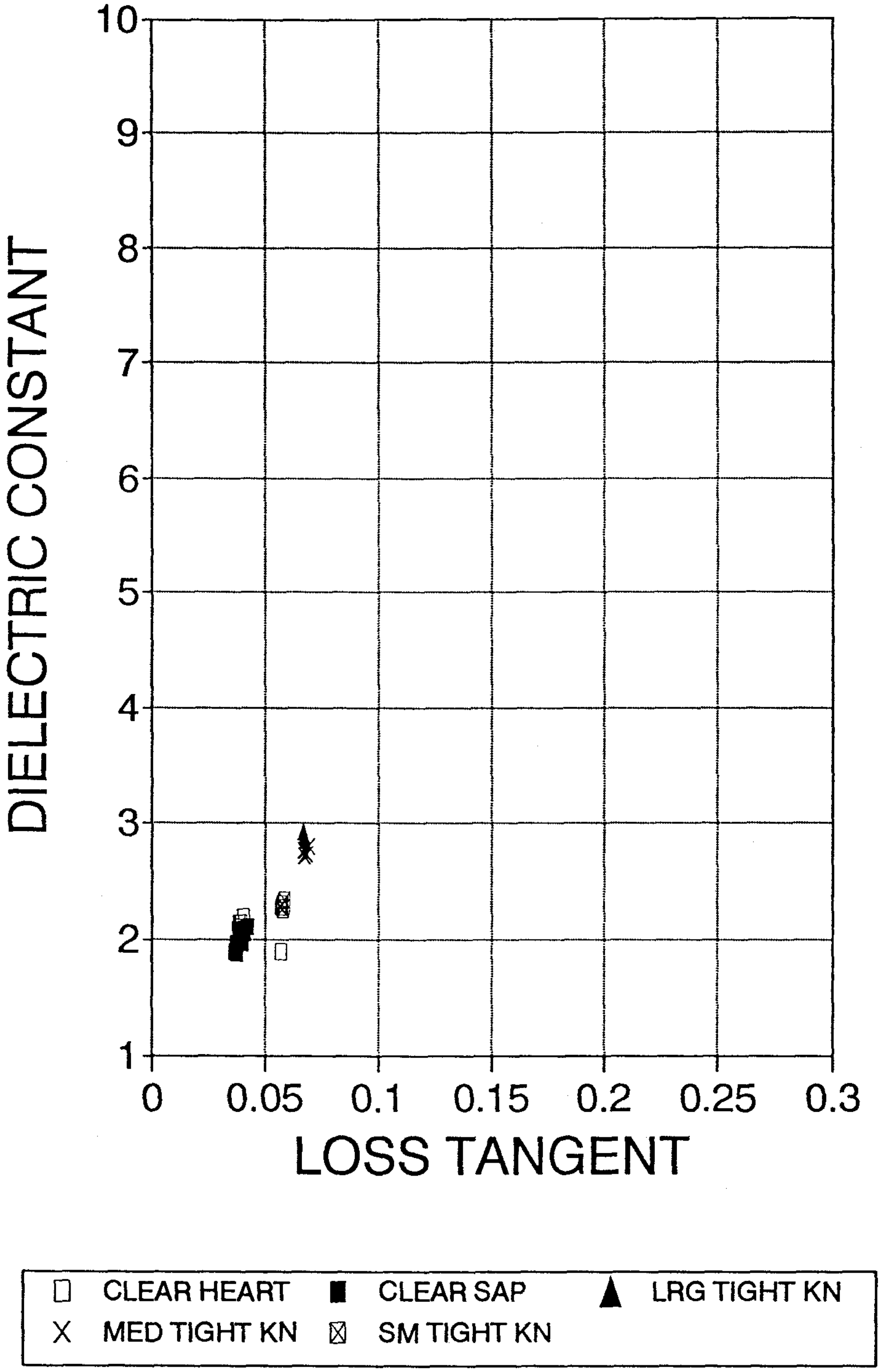

Figure 5.7. Preliminary experiment: The behavior of the dielectric constant and loss tangent of various wood features at 0% MC and 10 MHz.

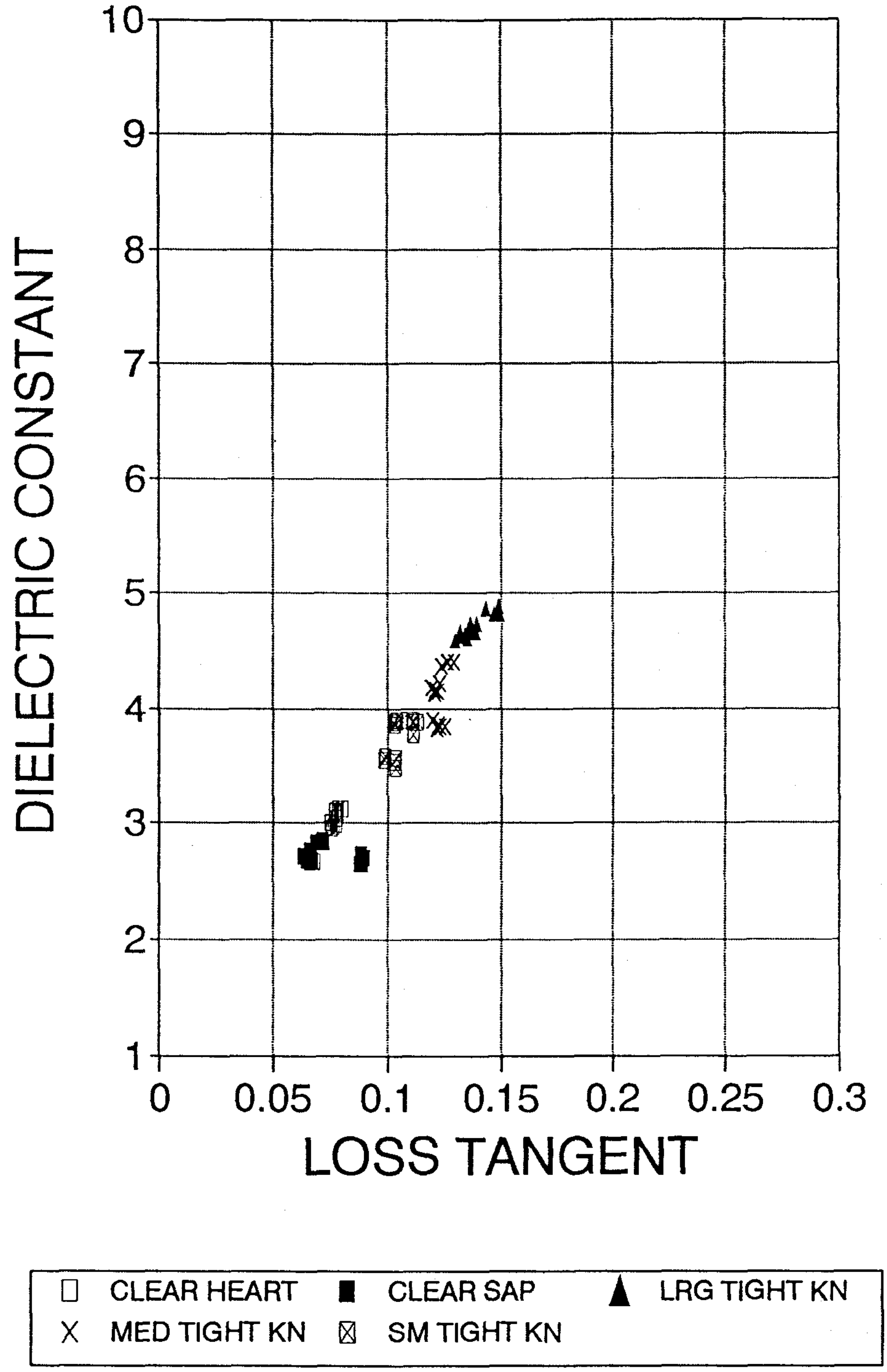

Figure 5.8. Preliminary experiment: The behavior of the dielectric constant and loss tangent of various wood features at 10% MC and 10 MHz.

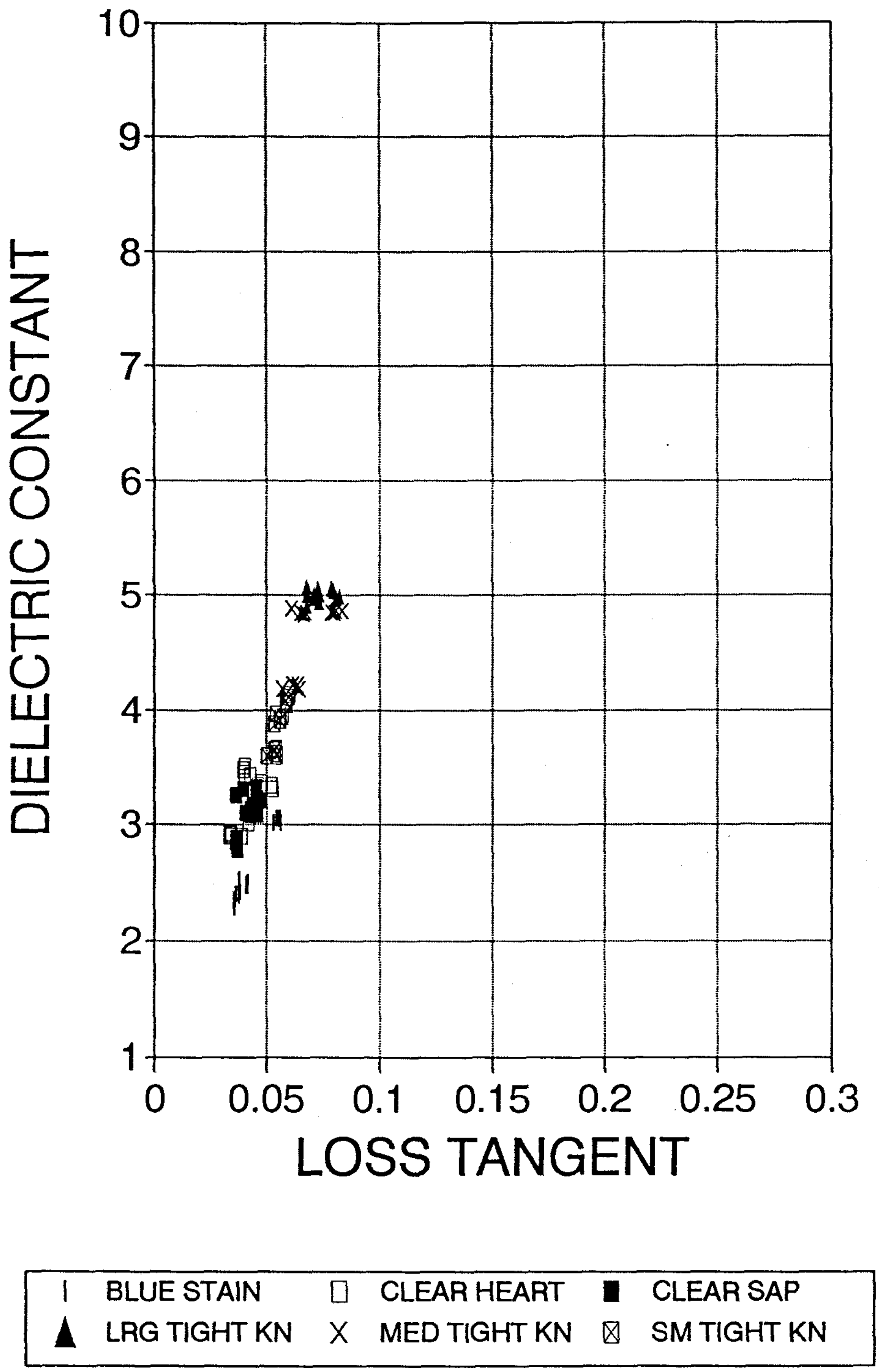

Figure 5.9. Preliminary experiment: The behavior of the dielectric constant and loss tangent of various wood features at 10% MC and 1.4 MHz.

Table 5.4. Separability of heartwood and sapwood by frequency and moisture content using the dielectric constant or loss tangent. "H+S" means heartwood and sapwood can be distinguished at the alpha=0.05 level; "HS" means that there is no apparent distinction at the alpha=0.05 level. Tests were conducted using the SAS GLM ANOVA procedure and Duncan's multiple range test.

DIELECTRIC CONSTANT					
MC (%)	FREQUENCY (MHz) 1.4	4	10	20	49
0	H+S	H+S	H+S	HS	H+S
6.6	H+S	H+S	HS	HS	H+S
10.0	HS	H+S	HS	HS	H+S
20.0	H+S	HS	HS	H+S	H+S
LOSS TANGENT					
0	HS	HS	HS	HS	HS
6.6	HS	HS	HS	HS	HS
10.0	HS	HS	HS	HS	HS
20.0	HS	HS	HS	HS	HS

5.5.5 Detectability of various sizes of tight knots

The ranges of dielectric constants for tight knots are given in Table 5.5. There are larger differences between dielectric constants for the same frequency range for larger knots than for smaller knots and this effect is uniformly enhanced at higher moisture contents. Although the numerical magnitudes of these differences are small, a difference of 0.2 in the dielectric constant is within the capability of the instrumentation. Of further interest is the ratio between the knot and its surrounding clear material, which is a relative measure of contrast. It should be noted that the size of the knot has a direct influence on the magnitude of the ratio, with large tight knots being 2:1 and small tight knots 1.4:1. Moisture content has very little, if any, affect on the magnitude of these ratios. Frequency has little, if any, influence on the magnitude of these ratios.

Further comparison of the detectability of various sizes of tight knots by their means using the SAS GLM ANOVA procedure is given in Table 5.6.

Table 5.5. Ranges in dielectric constants for different sized tight knots at two moisture content levels and five frequencies. Actual minimum and maximum values for dielectric constant, the corresponding increase in dielectric constant, and the ratios between the knot and clearwood are shown.

Tight Knot size	MOISTURE 6.6%	CONTENT 10%
Large	4.25 - 3.5 Δ=0.75 2.1:1-1.9:1	5.2 - 4.25 Δ=0.95 2.0:1-1.8:1
Medium	4.0 - 3.4 Δ=0.6 1.6:1-1.5:1	4.8 - 4.0 Δ=0.8 1.7:1-1.6:1
Small	3.40 - 2.8 Δ=0.6 1.4:1-1.3:1	4.3 - 3.5 Δ=0.8 1.5:1-1.3

Table 5.6 indicates that no comprehensive distinction between large, medium, and small tight knots was possible at any moisture and frequency condition using either dielectric constant or loss tangent. It is, however, possible to distinguish between the pairs large/medium and small (all moisture levels, 10 or 20 MHz, using

the dielectric constant), or otherwise medium/small and large (all moisture levels, 49 MHz, using the dielectric constant or loss tangent). It is also evident that the dielectric constant appears to be a more useful measure for making these distinctions than the loss tangent.

Table 5.6. Separability of various sizes of tight knots at various frequencies and moisture content using the dielectric constant or loss tangent. "L+M+S" means large, medium, and small can be distinguished at the alpha=0.05 level; "LM+S" means that there is no apparent distinction between large and medium the alpha=0.05 level, however, small can be distinguished from these two. Similarly "L+MS" means that there is no distinction between medium and small, but the large can be distinguished from these. Tests were conducted using the SAS GLM ANOVA procedure and Duncan's multiple range test.

DIELECTRIC CONSTANT					
MC (%)	FREQUENCY (MHz) 1.4	4	10	20	49
0	LMS	LMS	LM+S	LM+S	L+MS
6.6	LMS	LM+S	LM+S	LM+S	L+MS
10.0	LMS	LM+S	LM+S	LM+S	L+MS
20.0	LMS	LM+S	LM+S	LM+S	L+MS
LOSS TANGENT					
0	LMS	LMS	LMS	LMS	L+MS
6.6	LMS	LMS	LMS	LMS	L+MS
10.0	LMS	LMS	LMS	LMS	L+MS
20.0	LMS	LMS	LMS	L+MS	L+MS

The ranges in loss tangent for different sized tight knots are presented in Table 5.7. It appears that larger knots have slightly higher loss tangents than smaller knots. Moisture appears to have little affect on the magnitude of loss tangent. However, there is a moisture and frequency interaction as shown by the shift in the frequency for the loss factor peak. It appears that moisture has little or no affect on the ratio for loss factor for knots vs. clearwood. There appears to be an increase in the ratio for loss factor for knots vs. clearwood for large knots.

Table 5.7. Range in loss tangent for different sized tight knots at two moisture contents. The values shown as the first line in the table are for 1.4 MHz, peak value, and 49 MHz respectively. The second line is the ratio for loss tangent for the knot vs. clearwood. The third line is the frequency corresponding to the peak in loss factor.

Tight knot size	6.6% moisture content	10% moisture content
Large	0.06 - 0.125 - 0.1 2.5:1 10 MHz	0.06 - 0.15 - 0.12 3.0:1 20 MHz
Medium	0.05 - 0.12 - 0.09 2.0:1 10 MHz	0.05 - 0.13 - 0.09 1.7:1 20 MHz
Small	0.048 - 0.1 - 0.075 2.0:1 10 MHz	0.048 - 0.11 - 0.08 2.0:1 20 MHz

No comparative data for the magnitude for loss factor of knots could be found in the literature. James (1975) reported for Douglas-fir at 5.1% moisture content, 25°C, at and 10 MHz that the loss tangent ratio longitudinally to radially was 1.2:1. He showed an increase to 2.0:1 for the ratio at 12% moisture content. The results of this study thus indicate that the ratios for knots vs. clearwood for loss tangent are greater than for dielectric constant. In addition, these ratios are larger than that reported by James for longitudinal vs. radial fiber orientation. Therefore, it appears that there are other factors besides fiber orientation associated with knots that account for the larger ratio. Based on the literature, it could be theorized that the behavior of the loss tangent is a result of knotty material containing a greater proportion of a specific kind of bipolar substance that provides ready water bonding sites. However, further study is necessary to explore this concept.

5.5.6 The effect of density on the dielectric properties of clearwood

In this preliminary study, sample specific gravity (oven-dry weight, green volume), ranged from 0.42 (TKL1, 2 and 3) to 0.46 (TKM1, 2 and 3), and 0.49 (CLH1, 2 and 3). The dielectric constant has a positive correlation with both specific gravity and moisture content. It appears that this relationship may be nonlinear at 6.6% moisture content and approximately linear at 10% moisture content. Except for the above observations regarding linearity of relationships, Peterson (1960) found similar results for Douglas-fir at oven-dry and 12% moisture contents. He further found that these relationships were valid regardless of wood species. Peterson reported a power factor of 0.065 at 5 MHz at oven-dry and 0.055 at 12% moisture content for Douglas-fir. The results from this preliminary study are thus comparable to what Peterson reported, although the specific gravity for Douglas-fir in Peterson's results is somewhat higher (0.54) than that found in this study (0.49).

5.6 Summary and Conclusions

A dielectric spectrometer was constructed based on a revised version of Ichijo's (1953) design with revised methods for the determination of the dielectric constant and loss tangent. The dielectric constant calculation used an automated peak picking algorithm while the loss tangent measurement was based on the classical Q-measurement technique. The main advantage found for using Ichijo's approach was the ability to isolate the effects of very high loss dielectrics from the measurement circuitry. The revised dielectric spectrometer produced accurate and repeatable results in the range 1.4 - 49 MHz range. The accuracy was within 1.8% at 1.4 MHz, 0.33% at 10 MHz, and 0.79% at 20 MHz using a known test material and empirical calibration.

The preparation of wood samples from wet material needed to be avoided. The wetter samples showed a greater degree of mechanical instability due to the extra shrinkage that took place below fiber saturation. In addition, samples needed to be restrained while being conditioned to ensure that their surfaces remain parallel.

Although results from this experiment indicated that it would be possible to distinguish between heartwood and sapwood, this distinction could not be made reliably (Table 5.4). No conclusion regarding detecting blue stain was possible due to the extent that those samples warped. It does, however, appear that an operating frequency of 10 or 20 MHz gives the best possible chance for separating between features (Tables 5.4, 5.6).

6. EXTENDED EXPERIMENT

The preliminary experiment reported in Section 5 was designed to evaluate the dielectric spectrometer's full complement of frequencies. A limited feature sample set was evaluated to gain insight into how best to perform a larger experiment. This larger, more in-depth experiment is named the "extended experiment."

6.1 Objectives for the Extended Experiment

The objectives for the extended experiment was to evaluate the dielectric properties using:

a) a broader set of wood features,

b) an extensive range of feature sizes, and

c) a larger statistical sample population with replicated samples within feature groups in addition to within sample replication.

6.2 Extended Experiment - Samples and Preparation

The sample set was composed of sixteen wood feature groups with each group represented by ten wood samples for a total of 160 samples. The full sample set, except for the heart/sap subgroup for clearwood, were investigated as shown in Table 6.1. Some features also have a size category such as small, medium, and large. Small in this context refers to features with dimensions smaller than the 0.75

inch sensor, medium means the feature is approximately 0.75 inch, and large is for features greater in size than the sensor. Certain features included a severity category such as heavy and light. For heavy and light blue stain classifications, WWPA (1988) grading rules are followed. Samples were cut to uniform thickness and parallel surfaces using a fine-toothed circular saw and a special jig. Smooth surfaces were produced using this method that required no further sanding or planing.

Table 6.1. Feature set and sample types for the extended experiment.

1. Loose knots: Group 1: Small loose knots $\leq 3/4''$ Group 2: Medium $3/4'' \geq$ loose knots $\geq 1/4''$ Group 3: Large loose knots $> 3/4''$
2. Tight knots: Group 4: Small tight knots $\leq 3/4''$ Group 5: Medium $3/4'' \geq$ tight knots $\geq 1/4''$ Group 6: Large tight knots $> 3/4''$
3. Open holes: Group 7: Small open holes $\leq 3/4''$ Group 8: Medium $3/4'' \geq$ open holes $\geq 1/4''$ Group 9: Large open holes $> 3/4''$
4. Pitch pockets: Group 10: Small pitch pockets Group 11: Large pitch pockets
5. Pitch streaks: Group 12: Light pitch streaks Group 13: Heavy pitch streaks
6. Blue stain: Group 14: Light blue stain Group 15: Heavy blue stain
7. Clearwood: Group 16: Clearwood

Similar to the preliminary experiment, an attempt was made to limit variation of basic wood properties within each feature group. However, for the extended experiment, each sample was prepared from a separate, independently selected block of wood. These blocks were cut from kiln-dried boards. Each block of wood measured approximately eight inches in length oriented in the longitudinal fiber direction. Sample strips measuring six inches long and 2 inches wide were cut from these blocks. These dimensions were chosen because specially-designed sampleholders were constructed to hold the test specimens so they were adequately restrained to maintain parallel surfaces over the duration of the experiment. The restraining devices were designed to prevent the sample warpage problem that was experienced in the preliminary experiment. During machining, an effort was made to obtain a tangential cut. The thickness of each sample was approximately 0.1 inch. However, that dimension was remeasured each time a dielectric measurement was taken to adjust for thickness swelling or shrinkage.

Basic wood properties for each block were determined by taking a one inch cross section from each end of the block at the time that the samples were cut. The two readings were averaged to provide a single value for the block. Properties measured included the number of rings per inch and the wood density (ASTM D2395-83 method B - volume by water immersion).

6.3 Test Frequencies and Moisture Contents

Three nominal levels of moisture content, 25%, 10%, and 6.6% were tested in the extended experiment. As in the preliminary experiment, these levels were reached by placing the samples in desiccators prepared with forced-air circulated, saturated salt solutions. For 6.6 % EMC, magnesium chloride was used, for 10% EMC manganese chloride was used, and for the 25% level sodium sulphate was used.

It should be noted that the test specimens were expected to be at a moisture content in the 8% to 12% range. Therefore, the first moisture conditioning phase was a desorption step, whereas the successive phases were sorption steps. Both the 6.6% and 25% levels are in the tails of the sorption isotherm, so equilibrium could only be attained after prolonged conditioning periods. Attaining the 25% EMC level was especially difficult. The measurements were performed in a standards room maintained at a nominal ambient temperature of 72°F (22.2°C) and 50 percent relative humidity.

After the test specimens were machined to the correct dimensions, they were clamped down in sample holder racks, 10 samples to a rack, and the racks placed into the desiccators, two racks to a desiccator. The actual moisture content history of the entire sample collection is presented in Figure 6.1, where the extent that the samples attained the target moisture content can be seen. As was the case in the preliminary experiment, a smaller amount of spread in actual sample moisture content is evident at the lower target moisture contents (6.6% and 10% MC) than at the highest moisture nominal content level (25% MC).

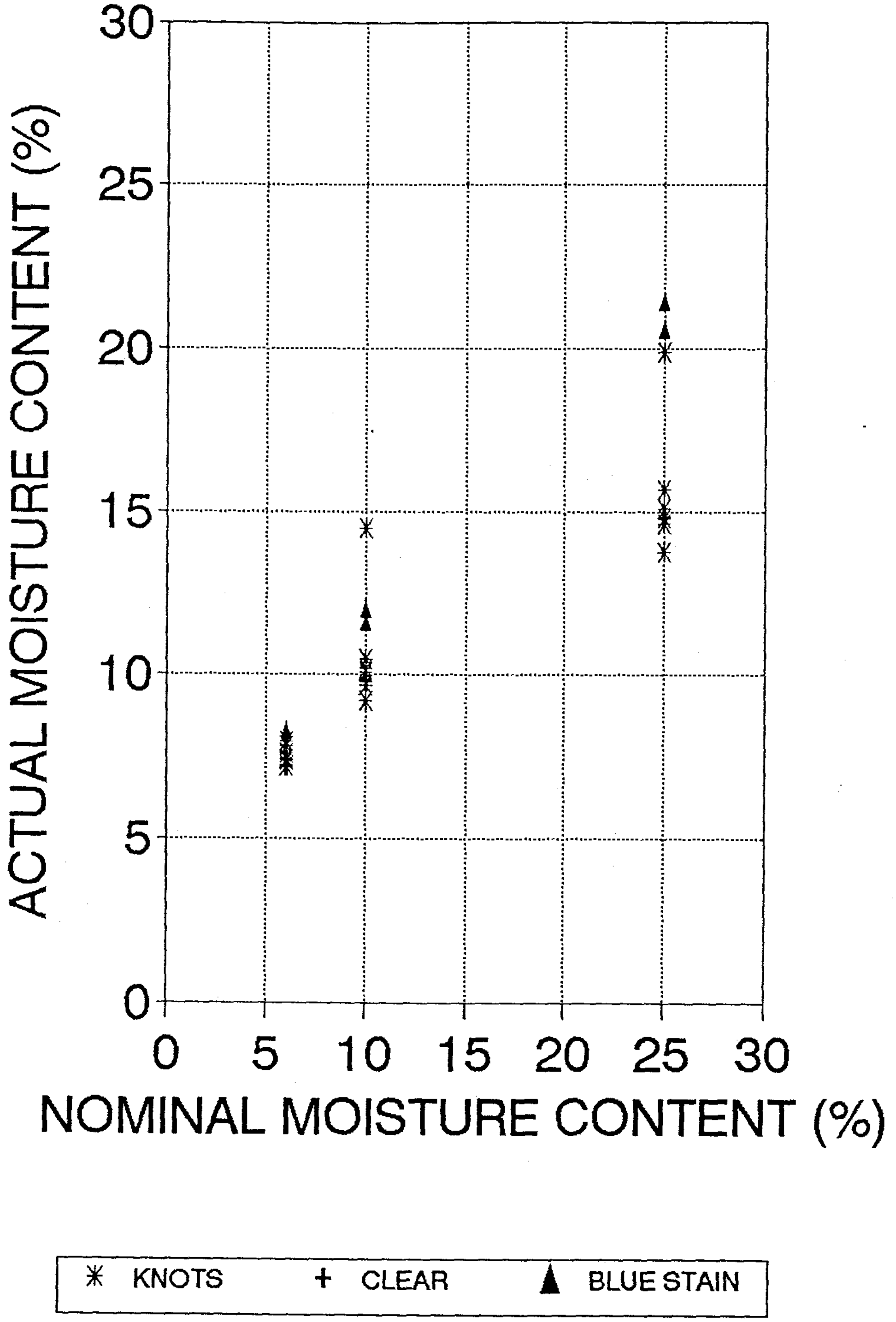

Figure 6.1. Extended experiment: Actual and nominal moisture contents for sample set.

At the 25% EMC level, the clearwood and blue stain samples achieved relatively higher moisture contents than did the samples containing knots. At each moisture content level (6.6%, 10%, and 25%), dielectric measurements were taken at three frequencies (1.4 MHz, 10 MHz, and 20 MHz). Each measurement was replicated three times so the total number of measurements was 4320 (16 feature groups, 10 samples per group, 3 moisture levels, 3 frequencies, and 3 measurement replications).

The procedure followed was to first achieve the desired moisture level and then to perform measurements on the entire sample set at one frequency level before changing to the next frequency level. Therefore, the measurements at each moisture level extended over several weeks. Because of this prolonged period at a particular moisture level, test specimens were promptly returned to the appropriate desiccator after measurements were taken, thus allowing them to regain equilibrium before the next round of measurements. Due to the nature of the wood sorption isotherm, the time to reach equilibrium between moisture levels varied according to the target level.

6.4 Statistical Design and Analysis

When evaluating the appropriateness of various statistical analyses for this experiment, there were a number of sources of experimental error. An assessment of the variability in measurements due to the instrumentation is presented in Appendix 2: "Dielectric Spectrometer - Calibration and Repeatability." That analysis showed that the dielectric spectrometer was capable of repeatable and accurate measurements with low, random experimental error. Other sources of experimental error were due to the wood-sensor interface where variability was introduced by factors such as surface roughness, uneven wood swelling, or variable micrometer clamping pressure. In addition, physical parameters of the wood, such as density or the number of rings per inch, further increased the experimental error. The effects of the physical parameters will be presented in Section 6.5.3, where it will be shown that they introduced random variation. Experimental error was analyzed by replicated measurements and included in the statistical analysis as an independent factor.

The next step was to get a better understanding of the underlying mechanisms that drive the response variables, moisture content and frequency, as well as their interactions. First, an exploratory analysis of the raw data was done by plotting raw experimental dielectric data by moisture and frequency. The collection of graphs forming the basis for that analysis and is presented for completeness in Appendix 4: "Extended Experiment: Relationship Between Moisture Content and Frequency for Wood Features." Second, that set of graphs was then further condensed by plotting the dielectric constant against loss tangent for the entire set of features on one graph for each moisture content and frequency combination. These plots are presented in Figures 6.2 through 6.10, and they help in understanding how the dielectric constant and loss tangent are related through the Kramers-Kronig (KK) relation (MacDonald 1987; Jonscher 1983). Wood, however, as shown by the preliminary experiment (Section 5.5) and the literature (Trapp and Pungs 1956), shows the existence of a dipolar peak that occurs in the 10 to 20 MHz region. The effect of this dipolar peak, however, is complicated by an interaction between frequency and moisture content, especially in the 8% to 10% MC range. Figures 6.2 through 6.10 indicate how the KK relation may be considered having similarities to principal components analysis. However, instead of deriving Eigenvectors through the Karhunen-Loeve transform (KLT), the actual physical parameters, moisture content and excitation frequency, are manipulated to find the ideal set of working conditions for making good discrimination between wood features based on the values for the dielectric constant and the loss tangent. However, without developing a model that can compensate for the effect that the actual moisture content plays on the dielectric parameters, there is no statistical measure available that can provide numerical justification why a certain combination is preferable over another. This is a judgement call. It will be shown in Section 6.5, that there is strong evidence that the strongest relationship between the dielectric constant and loss tangent exists for moisture contents between 10% and 20% MC and frequency between 10 MHz and 20 MHz. In this research, these conditions are considered "ideal" for making comparisons between the means for dielectric constant or loss tangent. Third, using the "ideal" working set of conditions from above, simple classification schemes based on Duncan's multiple range tests on the dielectric constant and the loss tangent are provided (Section 6.5).

A typical analysis of variance for this experiment would test the ratio of between-group variation to within-group variation. In other words, it would test the null hypotheses that all wood feature groups have the same mean. A classical factorial design analysis with moisture content and frequency as main factors was considered. However, it was found inappropriate for two reasons. First, the experiment was unbalanced, because the number of observations in the cells is not equal. For example, the feature groups comprising knots and open holes each have 30 samples, while feature groups comprising pitch pockets, pitch streak, and blue stain each have 20 samples. Second, the moisture content was not appropriate as a fixed factor. The actual moisture contents obtained for the samples were closer to the lower target moisture levels than at the 25% moisture content level. Moisture content could thus not be used as a fixed factor in this analysis. However, an ANOVA based on the 6.6% and 10% nominal moisture content levels was considered to be reasonably accurate. That analysis then offered a set of comparisons of means for the different feature groups. The reduced ANOVA for the 6.6% and 10% moisture levels, as with the preliminary experiment, is a repeated measures analysis where each observation consists of 18 response variables (univariates) consisting of three levels of frequency, two levels of moisture content and three measurement replications.

6.5 Results and Discussion

For the extended experiment, the effect of frequency and moisture content on the relationship between the dielectric constant and the loss tangent is shown in Figures 6.2 through 6.10. For the preliminary experiment a similar relationship is shown in Figures 5.7 though 5.9 where the 0% MC condition is also provided. The results from the preliminary and extended experiments are similar. In general it is evident from these graphs that moisture content extends the variation of both dielectric content and loss tangent. The purpose of these plots was to help in understanding how the dielectric constant and loss tangent are related through the KK relation. Wood, as shown by the preliminary experiment (Section 5.5) and the literature (Trapp and Pungs 1956), shows the existence of a dipolar peak that occurs in the 10 to 20 MHz region. The effect of this dipolar peak, however, is complicated by an interaction between frequency and moisture content, especially in the 8% to 10% MC range. Evidently the strongest relationship between the dielectric constant and loss tangent exists for moisture between 10% and 20% and frequencies between 10 MHz and 20 MHz. Figures 6.6 (10% MC at 10 MHz) and Figure 6.10 (25% MC at 20 MHz) are examples that show a strong relationship between dielectric constant and loss tangent. Therefore, only these moisture and frequency combinations were considered for further analysis.

Tables 6.2 through 6.5 show Duncan's multiple range differences between means in dielectric constant and loss tangent for the "ideal" moisture content conditions (6.6% and 10% MC levels at 10 and 20 MHz). Note that Tables 6.2 to 6.5 have been composed from a reduced ANOVA where only 6.6% and 10% nominal MC data was used. At these moisture levels, Duncan's multiple range differences are considered reliable because there is close enough agreement between the nominal and actual moisture content levels for all wood features (Figure 6.1). Although Tables 6.2 through 6.5 list values for the means for the dielectric constant and loss tangents, these values should be used with caution. This is because of two reasons: First, the mean values for the features are based on an arbitrary size category. For instance, a large sized knots is a knot with a larger diameter larger than 3/4 inch, medium means the knot diameter is larger than 1/4 inch and less than

3/4 inch. Such size categories allow for a certain degree of variation in sizes and introduces variability in the means for the dielectric values that is unrelated to the dielectric behavior of the wood feature. If different criteria were used for the size categories, the mean values would most likely be different. In other words, there is a certain degree of bias in the reported values. Second, the physical size of the sensing head plays a role in the amount of wood substance that is sensed. A certain degree of integration over the wood surface takes place. The effect of the sensor's size will be more pronounced for larger sensors than for smaller ones. Such integration of dielectric properties can be complicated when the properties of the wood material under the sensor are inhomogeneous. I"n such cases the effective result should take Gauss' law for different dielectric properties into account. This observation is particularly valid for the means of wood features such as small knots, pitch pockets, and pitch streaks.

Due to the limited sample size (3) in the preliminary experiment, the ANOVA in Section 5.4 of the preliminary experiment did not consider within sample variation but rather within feature and between feature variation. The ANOVA for the extended experiment, however does include an analysis of experimental error due to within sample variation. The SAS (GLM) for the extended experiment's 6.6% and 10% MC data is shown in Table 6.6.

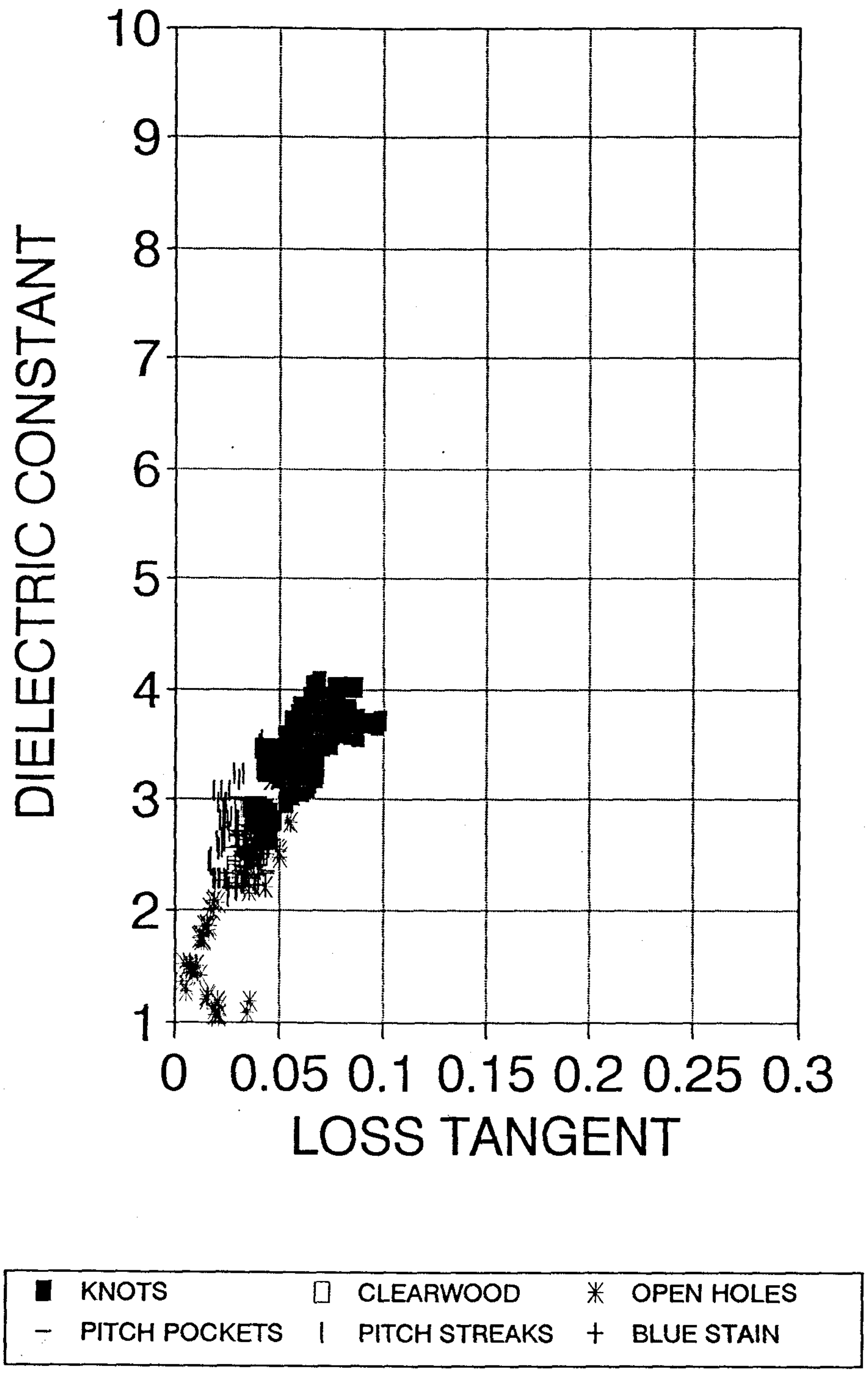

Figure 6.2. Extended experiment: The behavior of the dielectric constant and loss tangent of various wood features at 6.6% MC (nominal) and 1.4 MHz.

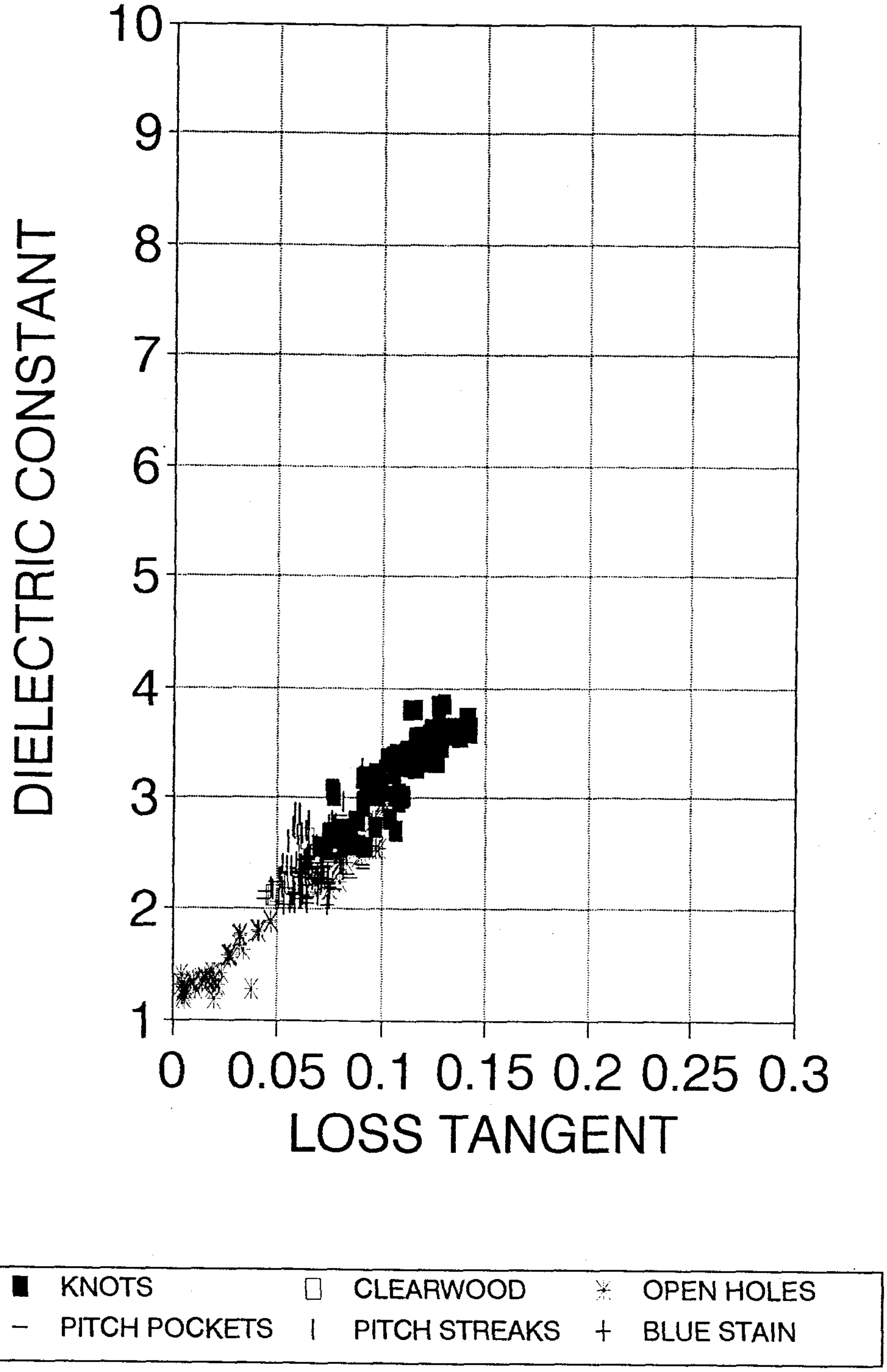

Figure 6.3. Extended experiment: The behavior of the dielectric constant and loss tangent of various wood features at 6.6% MC (nominal) and 10 MHz.

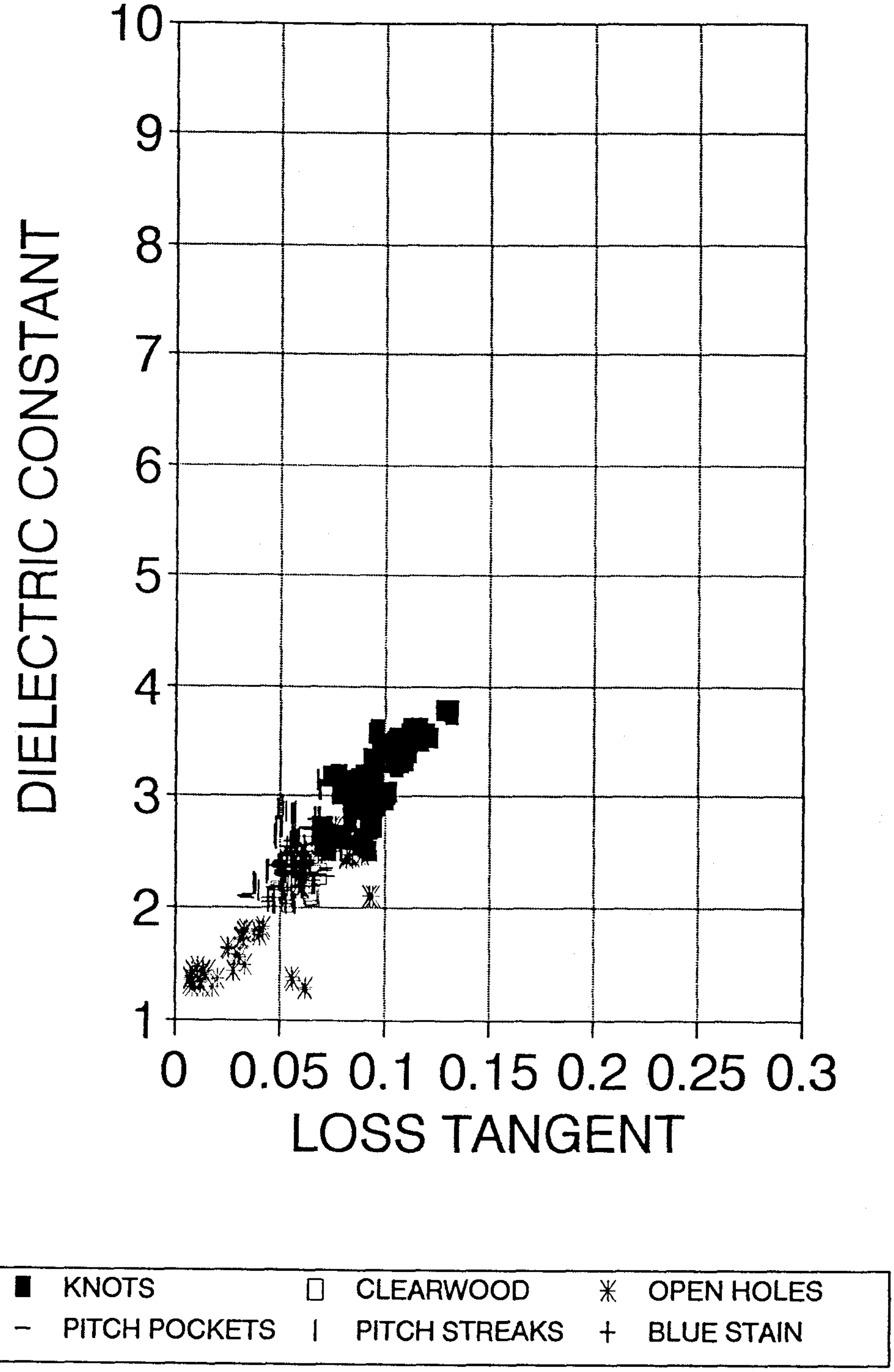

Figure 6.4. Extended experiment: The behavior of the dielectric constant and loss tangent of various wood features at 6.6% MC (nominal) and 20 MHz.

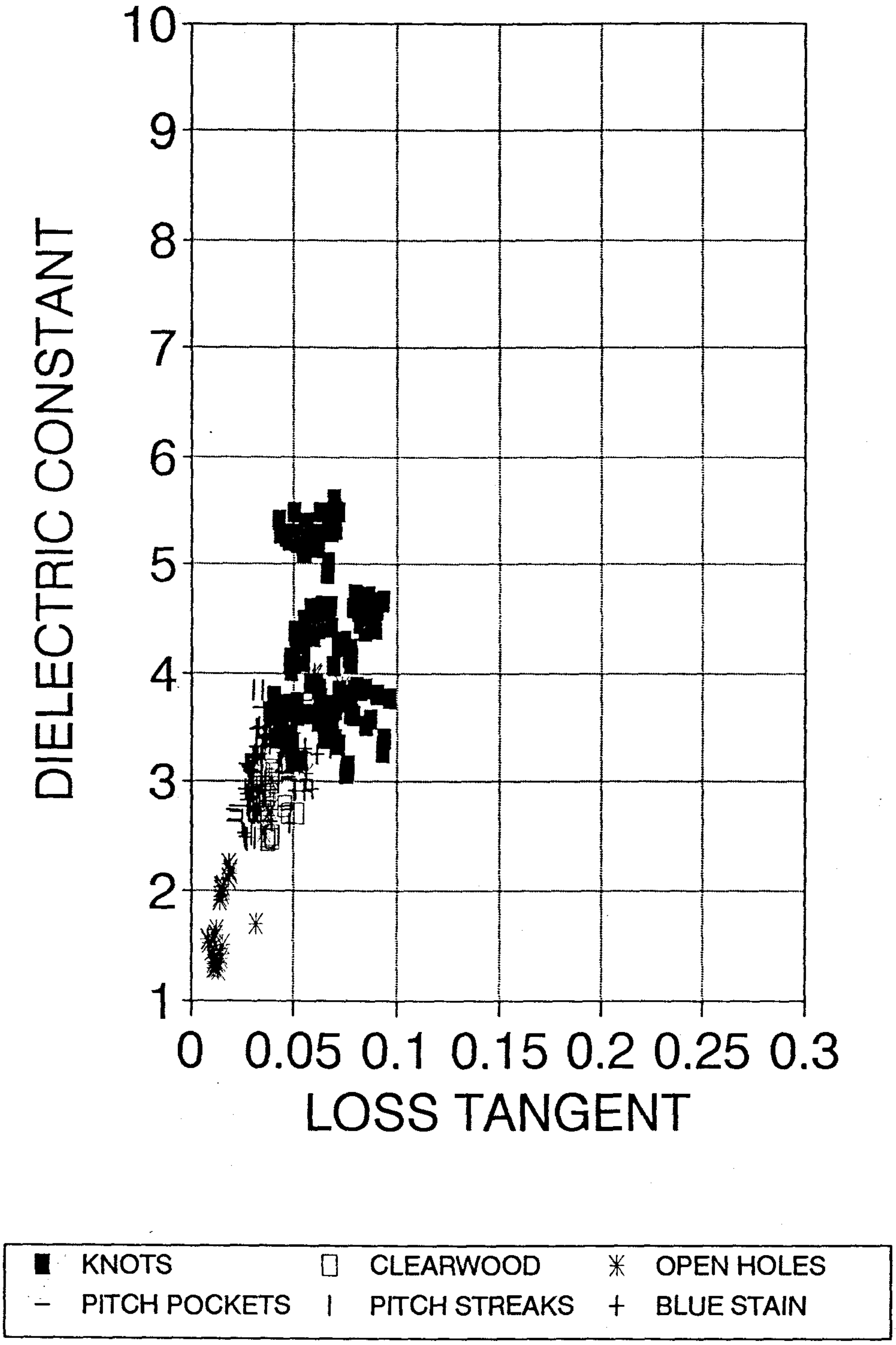

Figure 6.5. Extended experiment: The behavior of the dielectric constant and loss tangent of various wood features at 10% MC (nominal) and 1.4 MHz.

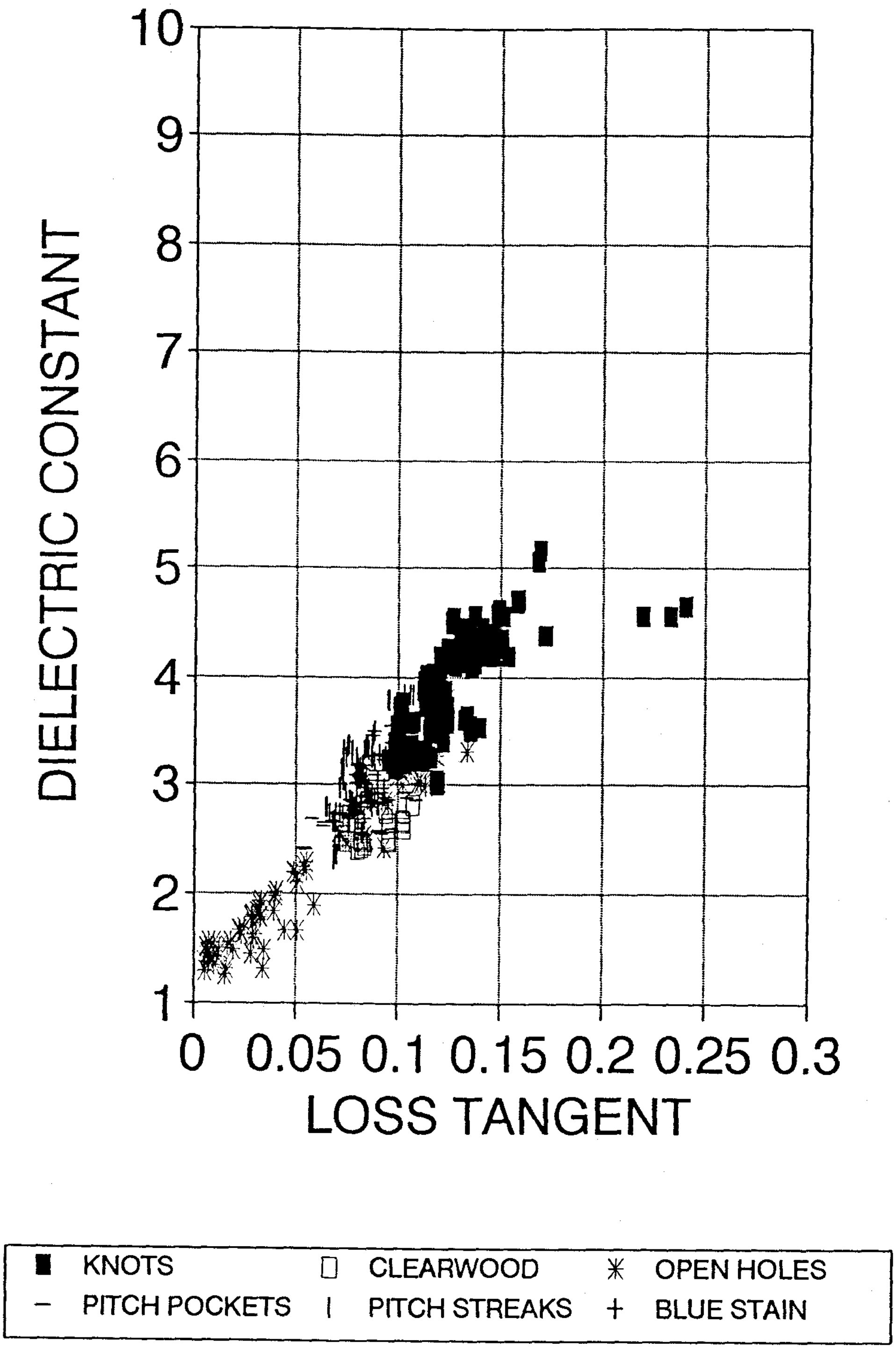

Figure 6.6. Extended experiment: The behavior of the dielectric constant and loss tangent of various wood features at 10% MC (nominal) and 10 MHz.

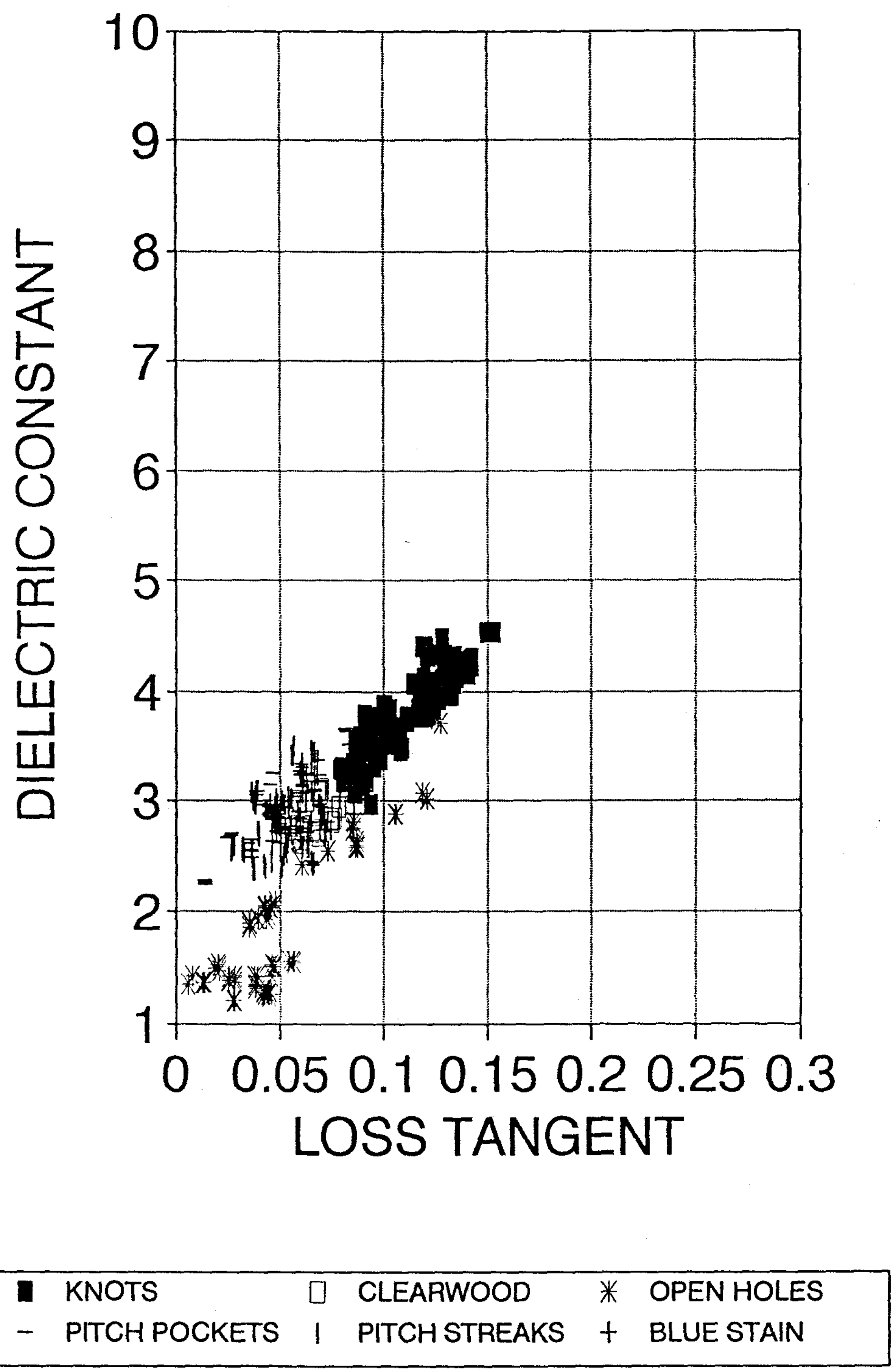

Figure 6.7. Extended experiment: The behavior of the dielectric constant and loss tangent of various wood features at 10% MC (nominal) and 20 MHz.

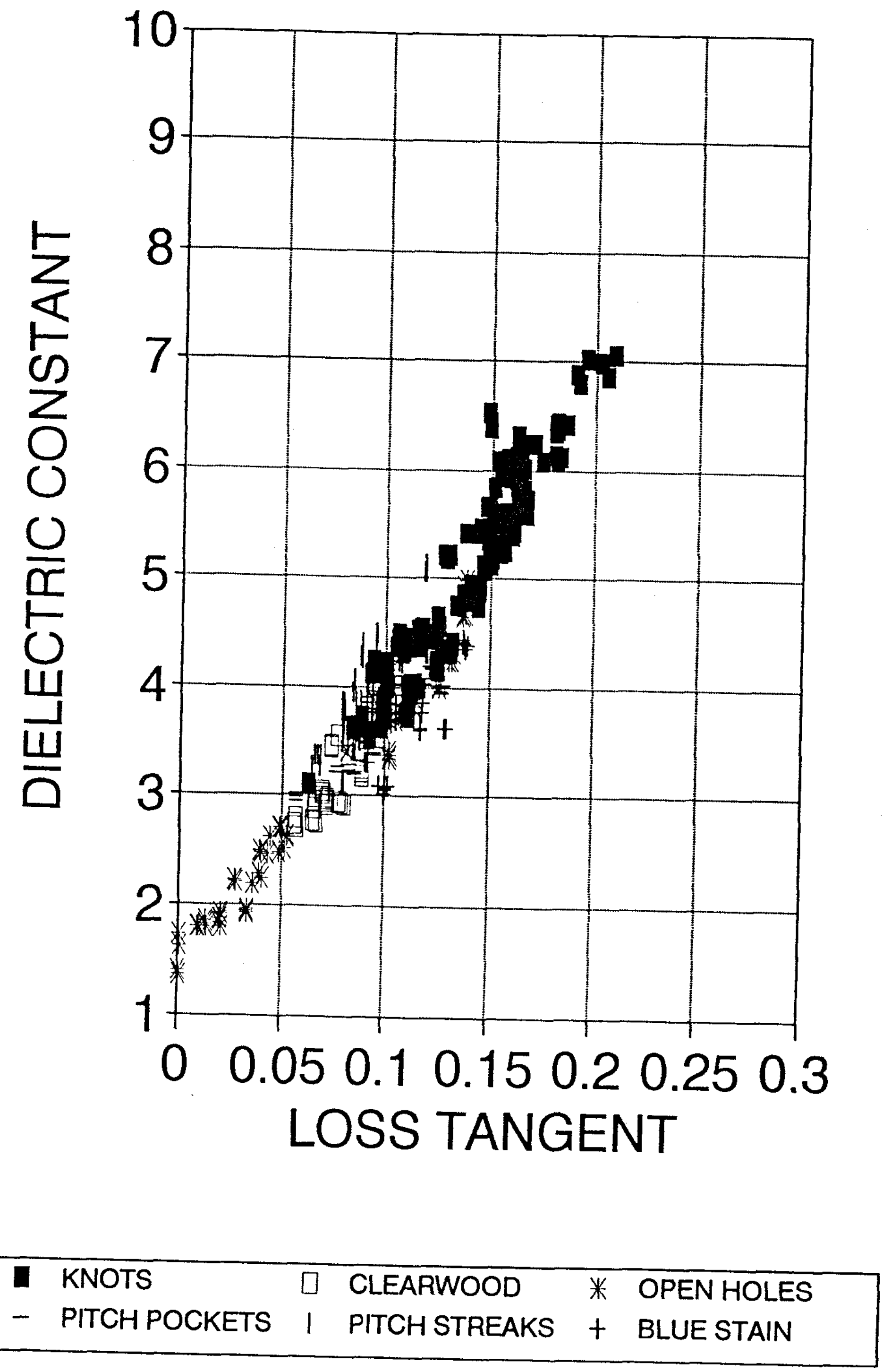

Figure 6.8. Extended experiment: The behavior of the dielectric constant and loss tangent of various wood features at 25% MC (nominal) and 1.4 MHz.

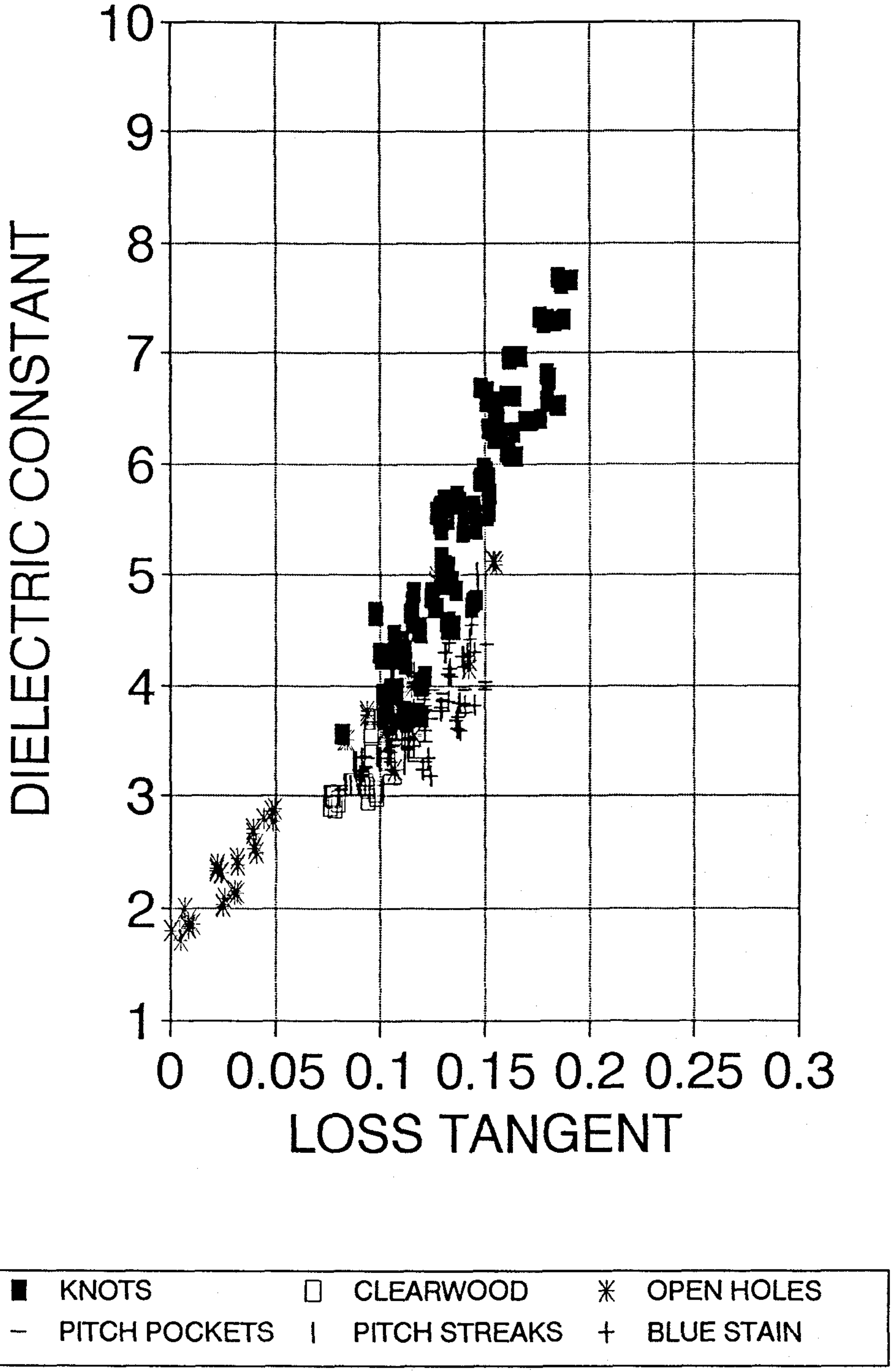

Figure 6.9. Extended experiment: The behavior of the dielectric constant and loss tangent of various wood features at 25% MC (nominal) and 10 MHz.

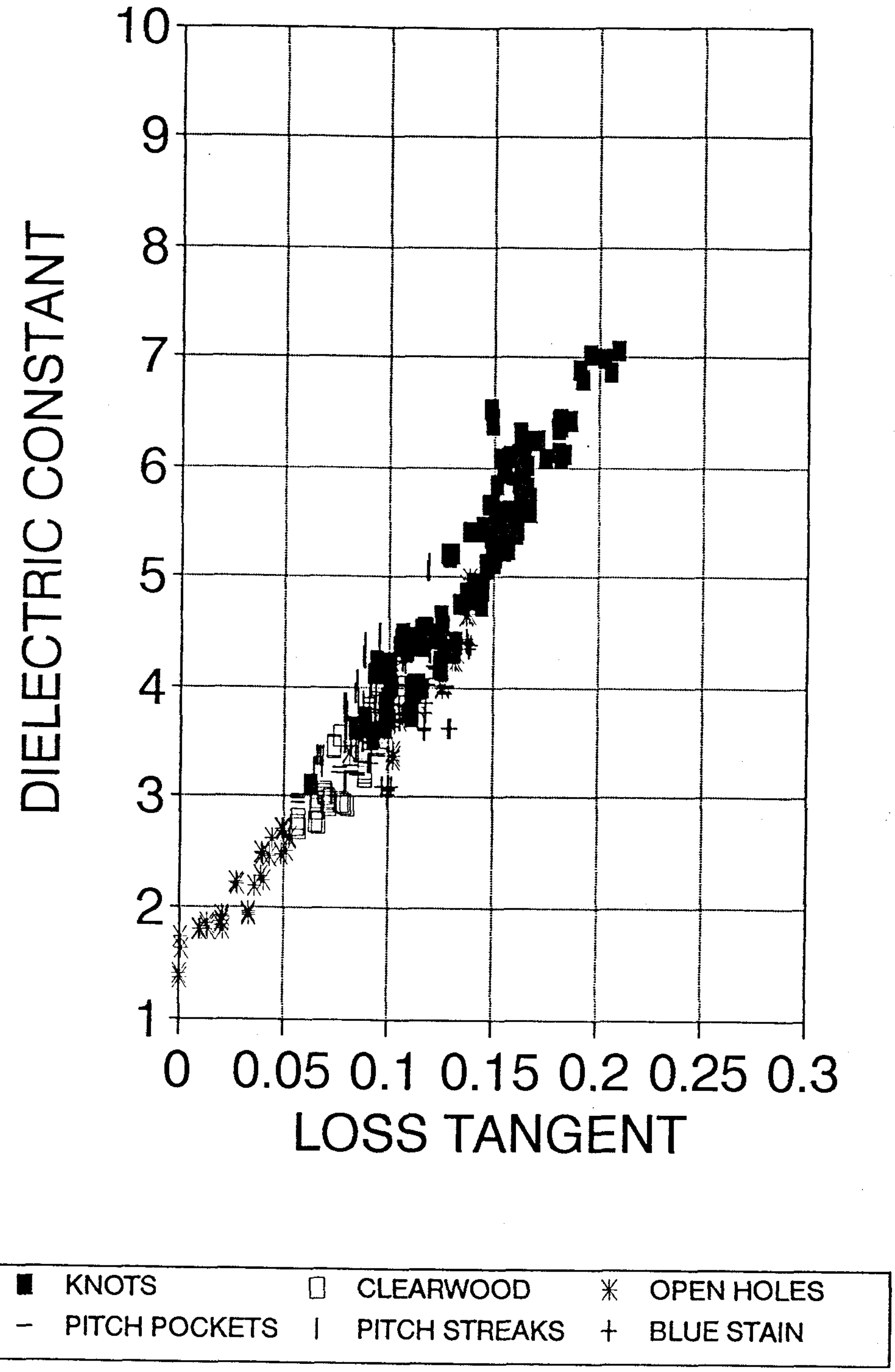

Figure 6.10. Extended experiment: The behavior of the dielectric constant and loss tangent of various wood features at 25% MC (nominal) and 20 MHz.

Table 6.2. Duncan's multiple range test results for the dielectric constant at 10% moisture content and a frequency of 10 MHz. (Statistical significance level of 0.05).

Duncan Grouping		Mean	GROUP
	A	4.4190	Large tight
	A	4.2880	Medium tight
	A	4.2880	Large loose
	A	4.1840	Medium loose
	B	3.5820	Small tight
C	B	3.3970	Small loose
C		3.2950	Heavy pitch streak
	D	3.0590	Light blue stain
	D	3.0170	Small open hole
	D	2.9920	Heavy blue stain
E	D	2.8360	Light pitch streak
E	D	2.8300	Large pitch pocket
E	F	2.7210	Small pitch pocket
	F	2.5700	Clearwood
	G	1.8570	Medium open hole
	H	1.4460	Large open hole

The ANOVA in Table 6.6 shows that there was no significant differences between the replicated point measurements (the factor "OBS" in Table 6.6), except where the excitation frequency interactions are considered. These cases, however, are not of concern, because measurements are taken at constant moisture content and frequency levels and not as independent random events.

As in the preliminary experiment reported in Section 5.4, the extended experiment shows that the effects of feature type, moisture content, frequency and their interactions are significant at the 95% confidence level and shows that there are significant differences between features under the different moisture and frequency conditions.

Table 6.3. Duncan's multiple range test results for the dielectric constant at 10% moisture content and a frequency of 20 MHz. (Statistical significance level of 0.05).

Duncan Grouping		Mean	GROUP
	A	4.1470	Large tight
	A	4.0880	Medium tight
	A	4.0560	Large loose
	A	3.9480	Medium loose
	B	3.5350	Small loose
	B	3.4220	Small loose
	C	3.1880	Small pitch pocket
	C	3.0080	Small open hole
D	C	2.9950	Heavy pitch streak
D	C	2.9860	Light blue stain
D		2.9030	Heavy blue stain
D	E	2.7910	Clearwood
D	E	2.7680	Large pitch pocket
	E	2.6030	Light pitch streak
	F	1.7920	Medium open hole
	G	1.3270	Large open hole

The Duncan's multiple range test was used to test for differences between dielectric constant means for features and loss tangent means for features. The results for the preliminary experiment was reported in Tables 5.4 and 5.6 where it was shown that there was no clear distinction between clear heartwood and sapwood, also that large tight knots could be distinguished from medium and small tight knots.

Table 6.4. Duncan's multiple range test results for the loss tangent at 10% moisture content and a frequency of 10 MHz. (Statistical significance level of 0.05).

Duncan Grouping		Mean	GROUP
	A	0.150810	Medium tight
B	A	0.138950	Large loose
B		0.136890	Large tight
B	C	0.125330	Medium loose
	C	0.117260	Small loose
	C	0.115270	Small tight
	D	0.101840	Small open hole
	E	0.088010	Clearwood
	E	0.086980	Small pitch pocket
	E	0.085380	Heavy blue stain
	E	0.083540	Large pitch
	E	0.083290	Heavy pitch streak
	E	0.082710	Light blue stain
	E	0.081690	Light pitch streak
	F	0.038730	Medium open hole
	G	0.014810	Large open hole

Similar arguments regarding the restricted use of an ANOVA and the Duncan's multiple range tests, hold for extended experiment. Examples of the results of the Duncan multiple range test from the extended experiment for 10% MC at 10 MHz and 20 MHz are shown in Tables 6.2 through 6.5. These results are discussed in Section 6.6.

Table 6.5. Duncan's multiple range test results for the loss tangent at 10% moisture content and a frequency of 20 MHz. (Statistical significance level of 0.05).

Duncan Grouping		Mean	GROUP
	A	0.129860	Medium tight
	A	0.129450	Large tight
	A	0.124960	Large loose
	B	0.113190	Medium loose
	C	0.096810	Small tight
	C	0.095020	Small loose
	C	0.092500	Small open hole
	D	0.075450	Small pitch pocket
E	D	0.065600	Light blue stain
E	D	0.065340	Clearwood
E	F	0.054770	Heavy blue stain
G	F	0.047570	Light blue streak
G	F	0.047560	Heavy blue streak
G	F	0.043610	Large pitch pocket
G	H	0.039070	Medium open hole
	H	0.031370	Large open hole

6.5.1 Effect of moisture content

The effect of moisture content on a limited set of wood features was tested in the preliminary experiment as shown in Figures 5.3 through 5.6. The results for the extended experiment are in close agreement. Figures 6.2 through 6.10 summarize the effects of frequency and moisture content for the sample collection as a whole for the extended experiment (Appendix 4, Figures A.4.1 to A.4.96 are included for completeness to show the effect of moisture content and frequency in detail for each feature group). It is evident from Figures 6.2 to 6.10 that for most features (except medium and large open holes), an increase in moisture content increases the variation of the dielectric constant.

Table 6.6. ANOVA using the SAS general linear models procedure for 6.6% and 10% moisture content levels, three excitation frequencies, and 16 wood features.

Source	DF	SSE	MSE	F Value	Pr > F
GROUP	15	1529.86	101.99	124.28	0.0001
MC	1	205.96	205.96	2935.61	0.0001
MC*GROUP	15	34.36	2.29	32.65	0.0001
RF	2	20.14	10.07	259.71	0.0001
RF*GROUP	30	15.96	0.53	13.73	0.0001
RF*MC	2	0.61	0.30	8.53	0.0003
RF*MC*GROUP	30	14.26	0.48	13.24	0.0001
OBS	2	0.00	0.00	3.35	0.0366
OBS*GROUP	30	0.03	0.00	0.79	0.7739
MC*OBS	2	0.01	0.00	3.09	0.0472
RF*OBS	4	0.00	0.00	0.27	0.8966
RF*OBS*GROUP	60	0.11	0.00	1.62	0.0033
MC*OBS*GROUP	30	0.04	0.00	1.29	0.1521
RF*MC*OBS	4	0.00	0.00	0.10	0.9817
RF*MC*OBS*GROUP	60	0.05	0.00	0.79	0.8764
Total					
GROUP	144	118.18	0.82		
RF	288	11.17	0.04		
MC	144	10.10	0.07		
OBS	288	0.32	0.00		
RF*MC	288	10.34	0.04		
RF*OBS	576	0.63	0.00		
MC*OBS	288	0.33	0.00		
RF*MC*OBS	576	0.60	0.00		

It is also evident that the degree to which moisture content affects the variation differs by feature. Knots, for example, have a range in dielectric constant at 6% MC and 1 MHz of 2.5 to 4.1 (Figure 6.2), while at 25% MC and 20 MHz the range is approximately 3.5 to 7.1 (Figure 6.10). On a comparative basis, clearwood at 6% MC and 1.4 MHz has a dielectric constant of approximately 2.5 but a range of 2.6 to 3.5 at 25% and 20 MHz. In this instance, the dielectric constant magnitude for clearwood is less affected by an increase in moisture content than the knot samples.

6.5.2 Effect of frequency

The relationship between the dielectric constant and loss tangent for the preliminary experiment is shown in Figure 5.6 through 5.9. A similar relationship is shown for the data from the extended experiment, but is more distinct due to the larger sample set and size. For the extended experiment, the 10 MHz (Figures 6.3, 6.6, and 6.9) and 20 MHz (Figures 6.4, 6.7, and 6.10) conditions appear as the optimal conditions for discriminating between features based on the dielectric constant and loss tangent. As discussed earlier (Section 6.5), the dielectric constant and loss tangent are related through the KK relation. Wood, as shown by the preliminary experiment (Section 5.5), the extended experiment, and the literature (Trapp and Pungs 1956), shows the existence of a dipolar peak that occurs in the 10 to 20 MHz region. The effect of this dipolar peak, however, is complicated by an interaction between frequency and moisture content, especially in the 8% to 10% MC range. Evidently the strongest relationship between the dielectric constant and loss tangent exists for moisture between 10% and 20% MC and frequency between 10 MHz and 20 MHz. Figure 6.6 (10% MC at 10 MHz) and Figure 6.10 (25% MC at 20 MHz) show a strong relationship between dielectric constant and loss tangent.

Therefore, only these moisture and frequency combinations were considered for further analysis using the Duncan's multiple range tests. Tables 6.2 through 6.5 shows Duncan's multiple range differences between means in dielectric constant and loss tangent for the "ideal" moisture content conditions (6.6% and 10% MC levels at 10 and 20 MHz).

6.5.3 Effect of specific gravity and rings per inch

Skaar (1948) and Torgovnikov (1993) reported a definite relationship between specific gravity and dielectric properties. These examples from the literature, however, are for defect-free wood where wood density is accurately known at the location where the dielectric measurement are taken. In contrast, in the preliminary and extended experiments the data on wood density was collected from the general vicinity of each wood feature being studied. These values of density are most likely not representative of many of the wood features. Tangential sectioning of samples further complicated the role of wood density. In this instance, the section would be along parallel layers of springwood (lower density) and summerwood (higher density). Dielectric measurements then show a natural variability due to the alternate high and lower density regions that may be quite different than the overall specific gravity of the sample.

The relationship between the number of growth rings per inch and specific gravity was investigated in both the preliminary experiment (shown in Figure 5.1) and the extended experiment (shown in Figure 6.11). No apparent relationship exists even when the larger sample set used in the extended experiment. The effect of specific gravity on dielectric properties is further shown in Figures 6.12 to 6.17 for different levels of moisture content. The lack of any systematic pattern in any of these Figures suggests that no evidence of a relationship is evident.

6.6 Dielectric Classification for Wood Features

The ability of the dielectric spectrometer to distinguish among the different wood features is then based on what this research identifies as, "the ideal moisture content, frequency level" for dielectric measurements. This corresponds to levels 10% MC, 10 MHz (Table 6.2) or levels 10% MC, 20 MHz (Table 6.3). These tables show five general categories for the different wood feature groups. The differences between these groups are significant at the 95% confidence level. An example wood feature classification based on the dielectric constant is shown in Table 6.7. A nearly identical classification resulted at 20 MHz with minor differences in the overlapping categories "2" and "3". The classification for using loss tangent as the response variable is shown in Table 6.8.

Based on the statistical test results shown in Tables 6.2 and 6.4, an example classification for the dielectric constant is shown in Table 6.7 and for loss tangent shown in Table 6.8. There are, however, subtle differences between the 10 MHz and 20 MHz classifications based on the loss tangent (Tables 6.4 and 6.5). Without the existence of a good physical model, perhaps, the loss tangent is not a good basis for making such distinctions between wood features at this time. This is because the loss tangent behavior is much more complex than the behavior of the dielectric constant.

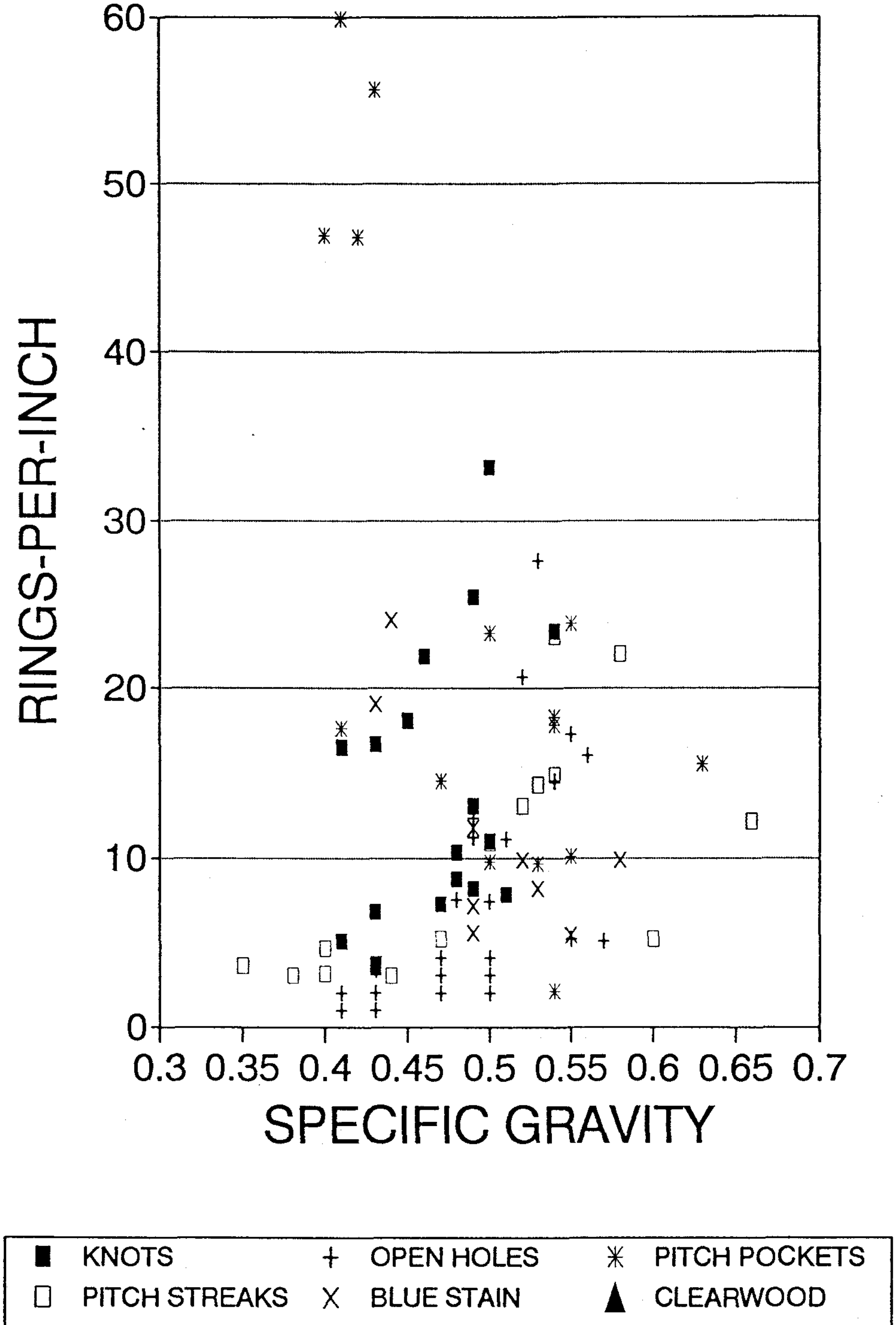

Figure 6.11. Extended experiment: Relationship between specific gravity and the number of rings per inch.

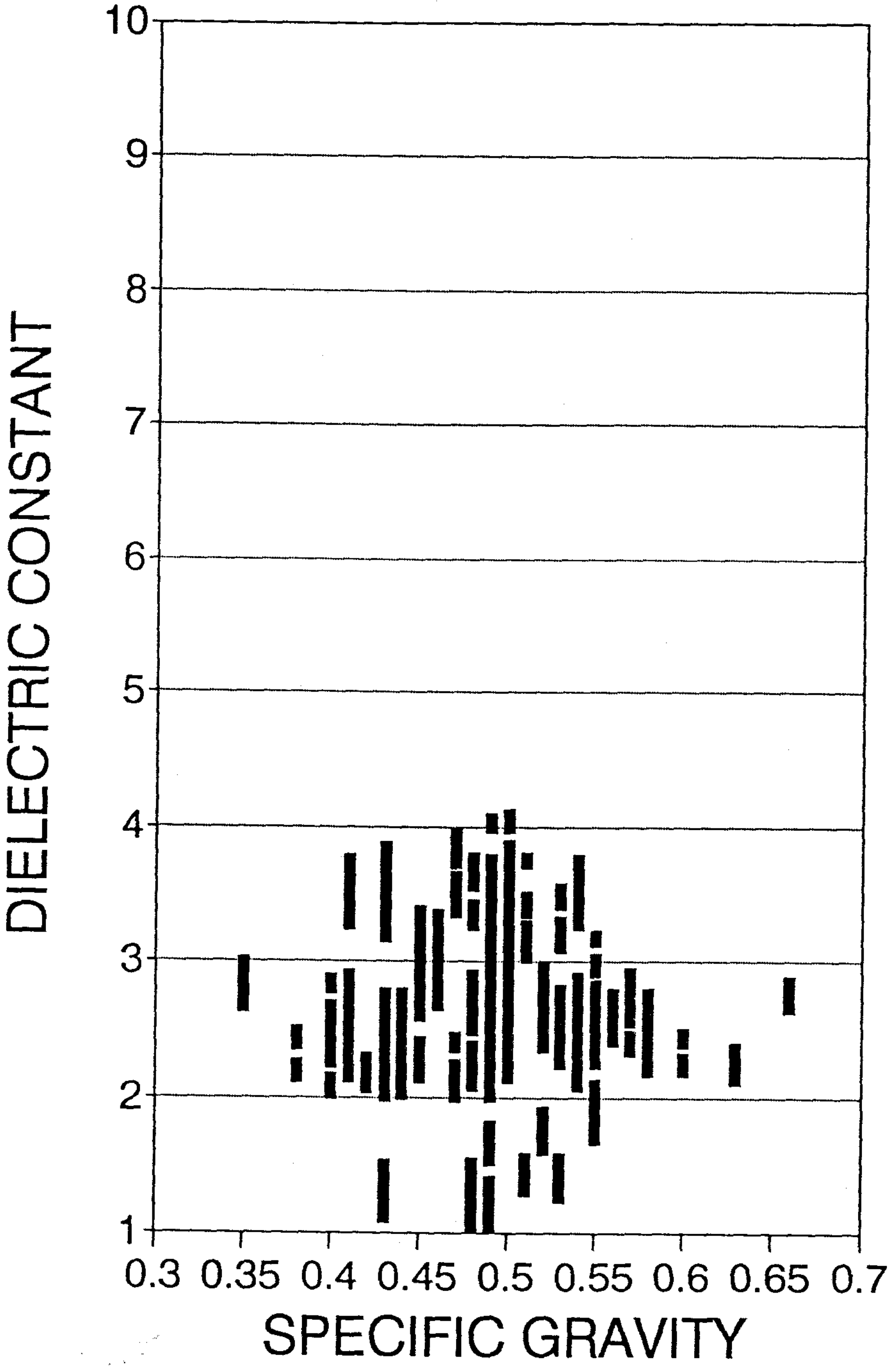

Figure 6.12. The effect of specific gravity on the dielectric constant at 6.6% MC (nominal).

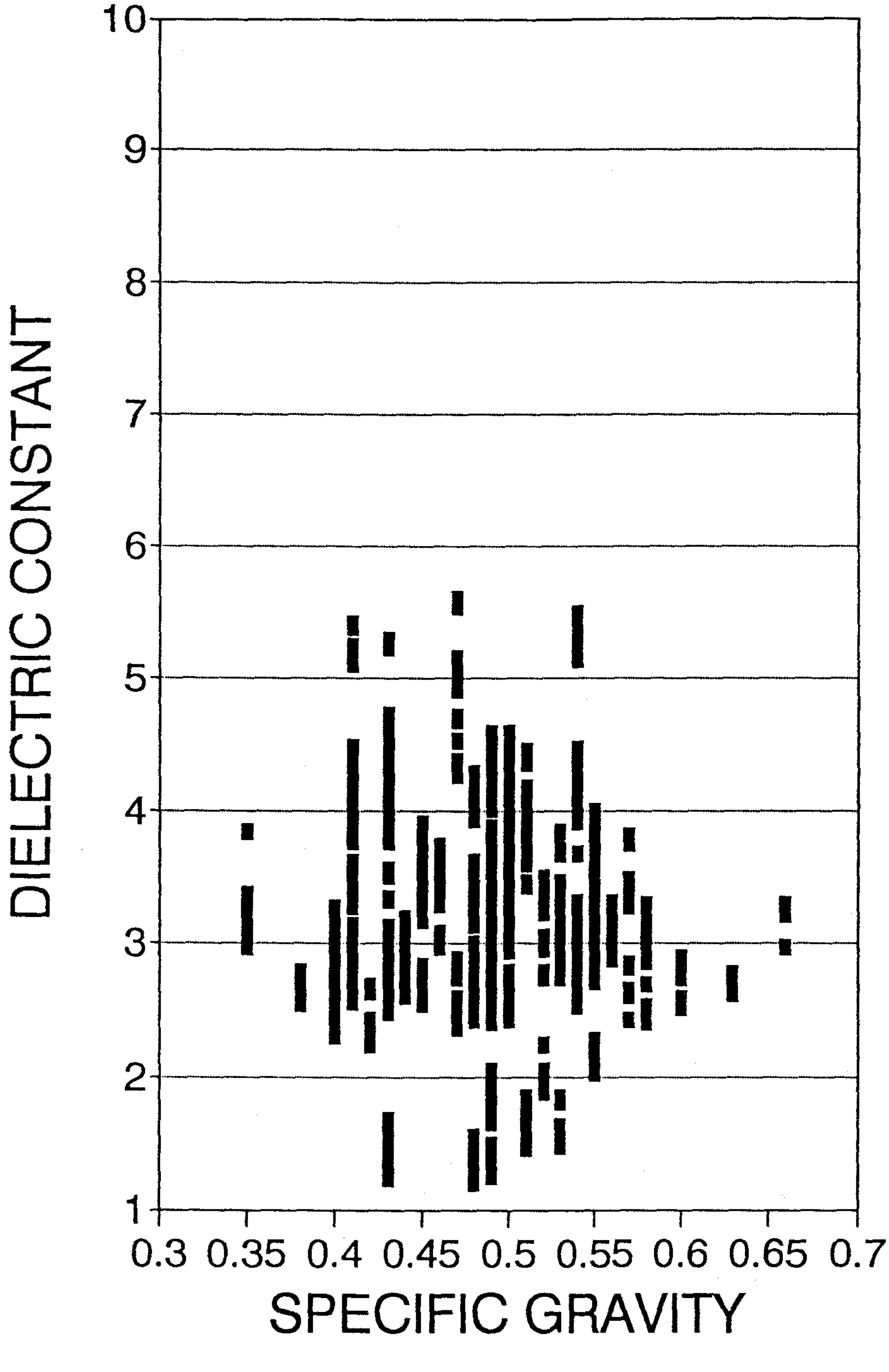

Figure 6.13. The effect of specific gravity on the dielectric constant at 10% MC (nominal).

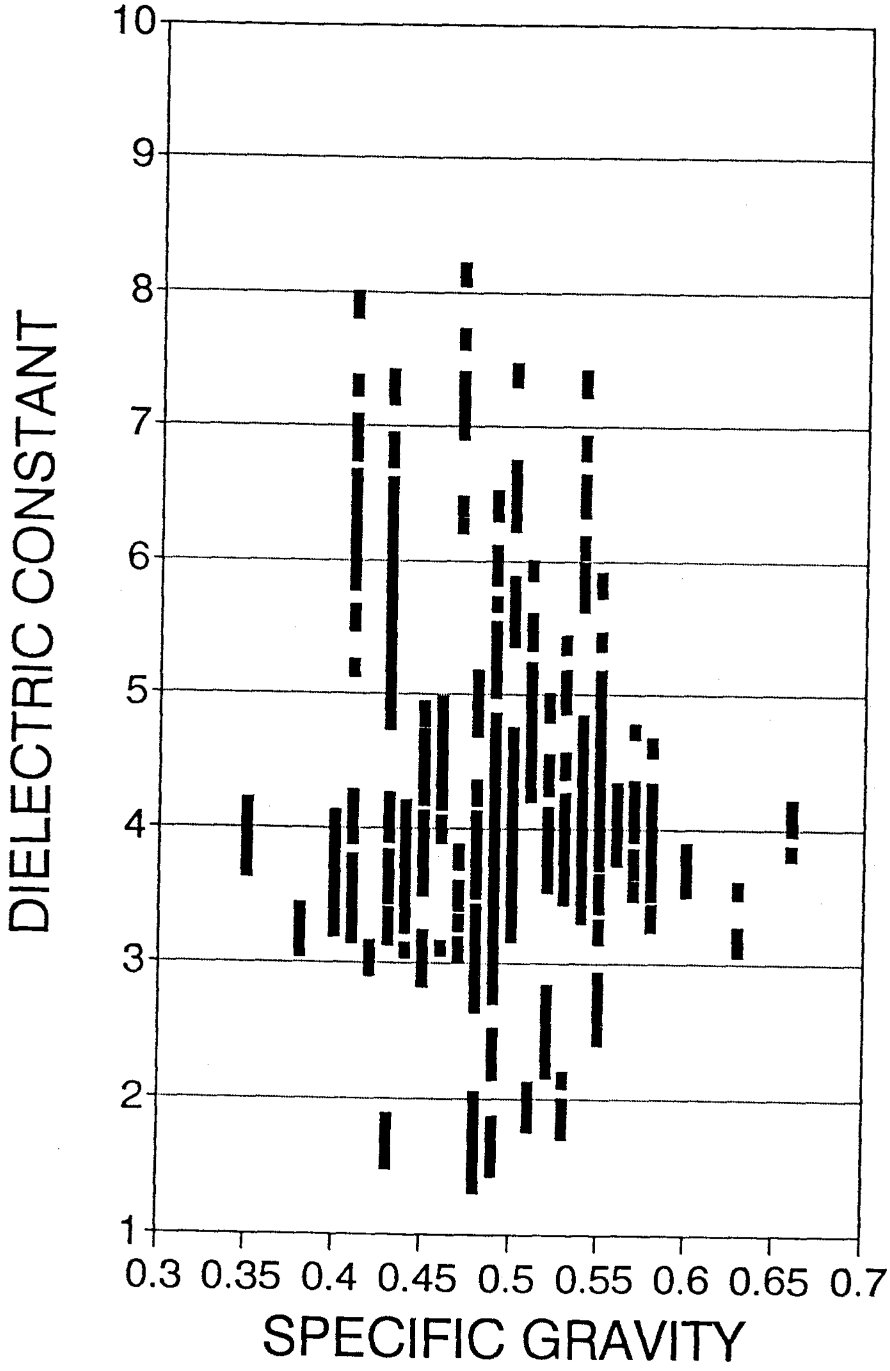

Figure 6.14. The effect of specific gravity on the dielectric constant at 25% MC (nominal).

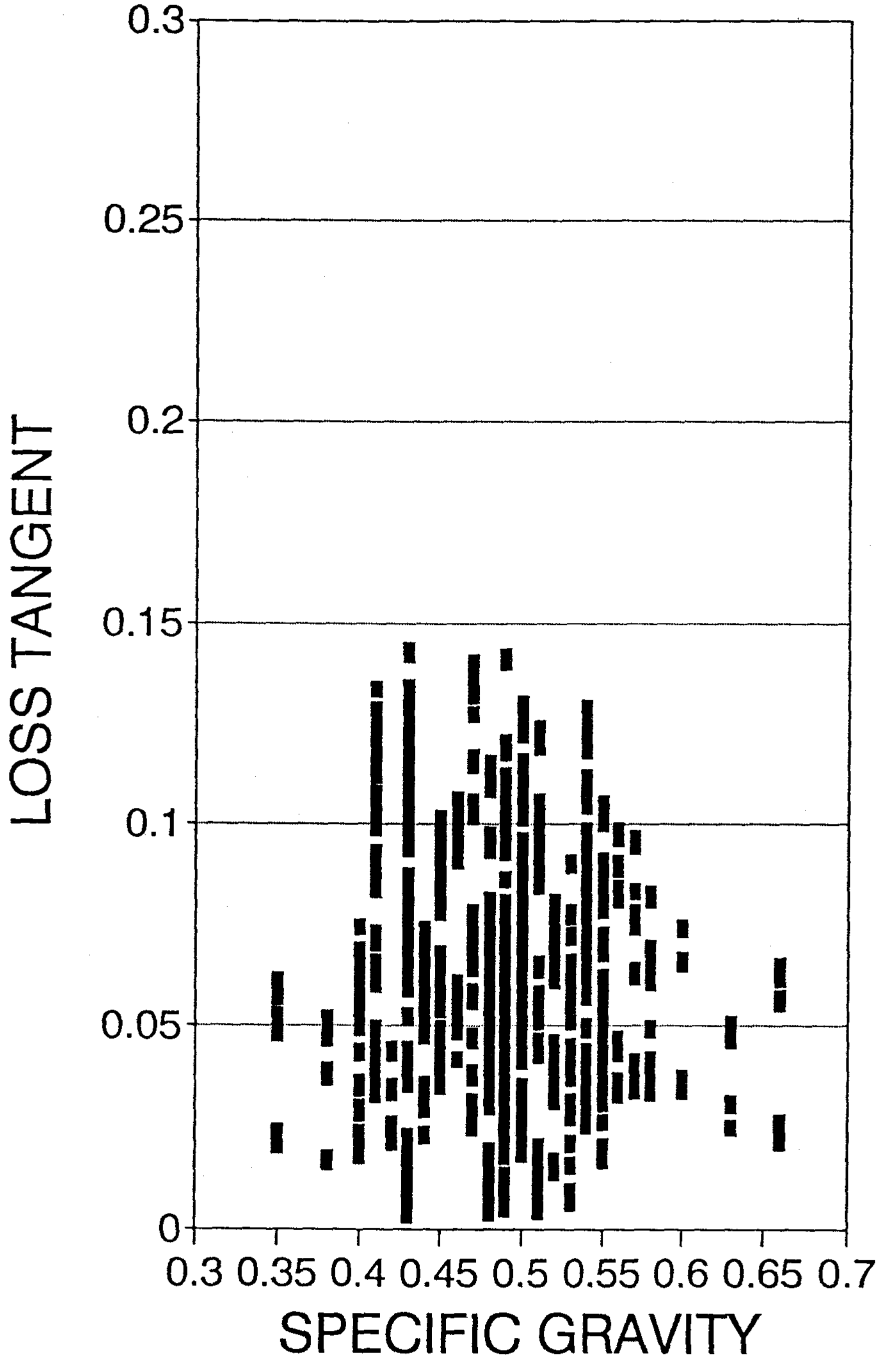

Figure 6.15. The effect of specific gravity on loss tangent at 6.6% MC (nominal).

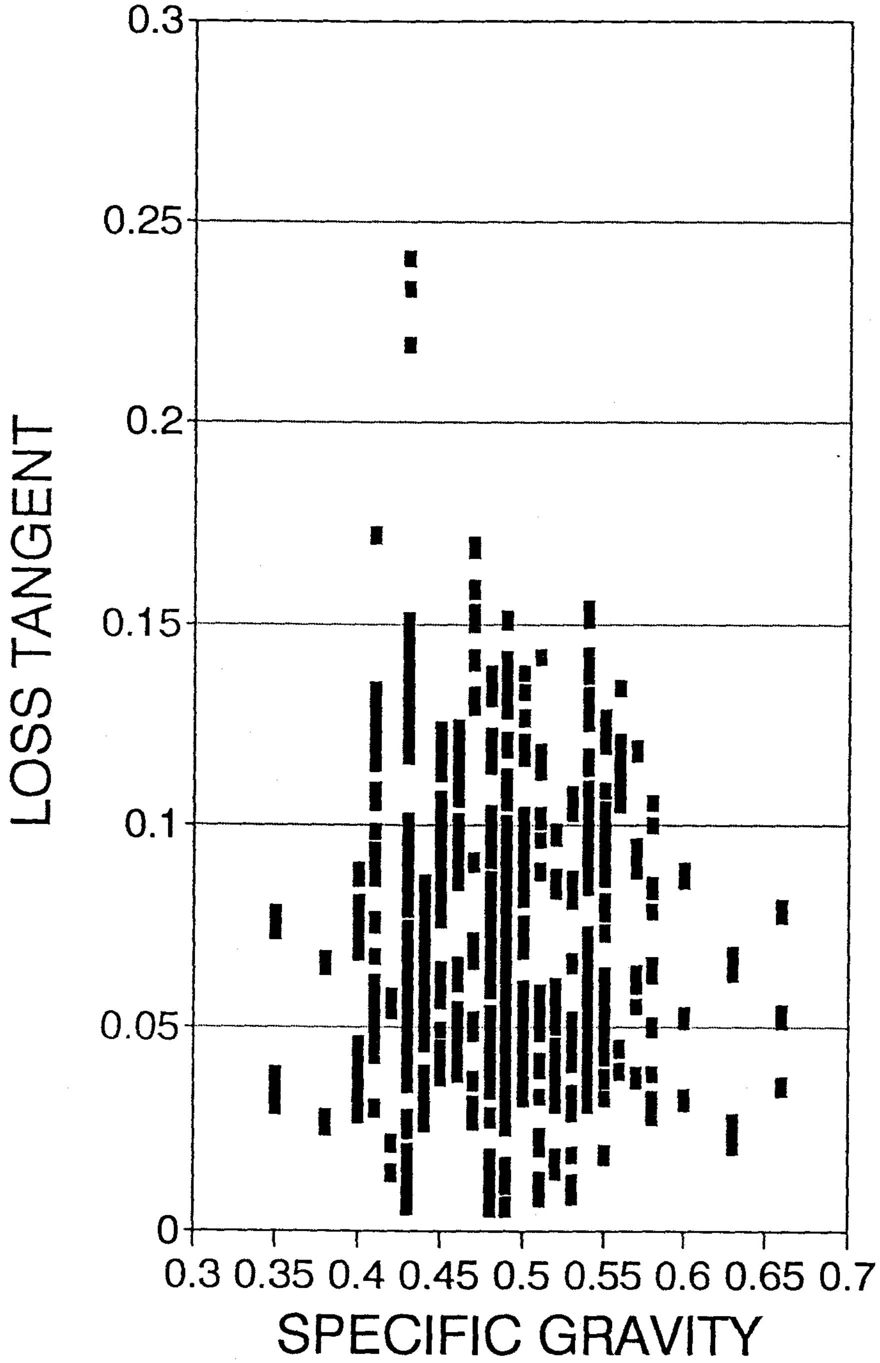

Figure 6.16. The effect of specific gravity on loss tangent at 10% MC (nominal).

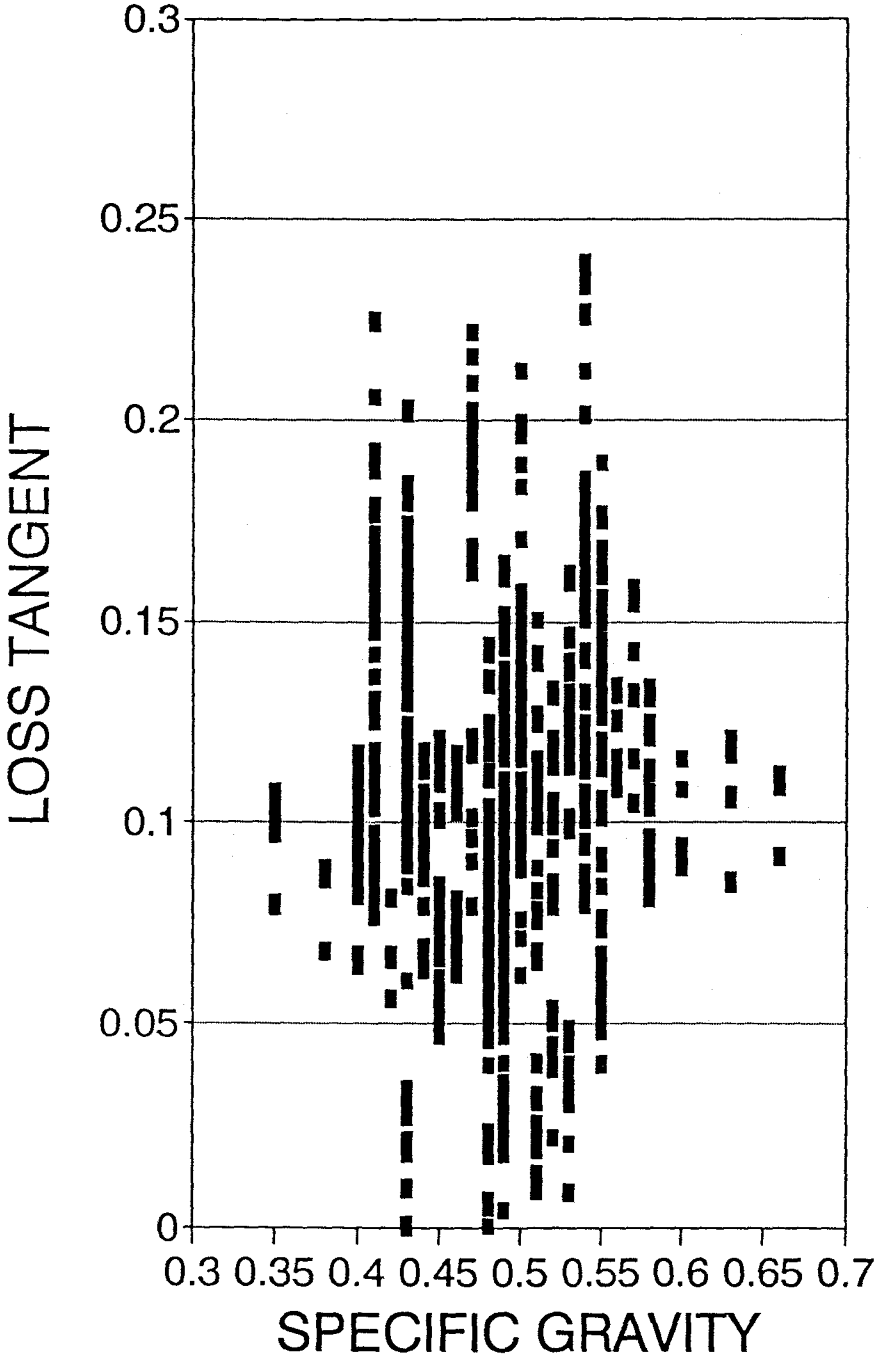

Figure 6.17. The effect of specific gravity on loss tangent at 25% MC (nominal).

Table 6.7. Dielectric constant classification for wood features at 10% moisture content and a frequency of 10 MHz.

1. Large and medium loose knots, large and medium tight knots.
2. Small tight knots, small loose knots, heavy pitch streaks.
3. Light and heavy blue stain, small open holes, light pitch streaks, large pitch pockets, small pitch pockets, and clearwood.
4. Medium open holes.
5. Large open holes.

Table 6.8. Loss tangent classification for wood features at 10% moisture content and a frequency of 10 MHz.

1. Small, medium, large loose and tight knots.
2. Small open holes.
3. Small and large pitch pockets, light and heavy pitch streaks, light and heavy blue stain, clearwood.
4. Medium open holes.
5. Large open holes.

Results from the preliminary experiment (Section 5.5) as well as the literature (Skaar 1948; Trapp and Pungs 1956; Brown et al. 1952) show that the dielectric constant gradually decreases in a predictable manner for an increase in frequency in the HF range. The loss tangent on the other hand, shows a complex interaction between moisture content by excitation frequency. Below approximately 6% MC, the loss tangent increases non-linearly for an increase in excitation frequency up to 10 to 20 MHz where there is a maximum. Beyond this frequency, the loss tangent then decreases with increased frequency. For moisture content levels above approximately 10%, the reverse situation holds. There the loss tangent becomes very large at frequencies below the HF range and decreases non-linearly to a minimum in the 10 to 20 MHz range. It is thus evident that when working with frequencies in the order of 10 MHz or moisture levels in the 8% to 10% range, the loss tangent may lead to distinctly different classifications.

7. SUMMARY, CONCLUSIONS, and FUTURE WORK

Previously, there was a lack of practical and theoretical knowledge of the electrical properties of wood defects. Therefore the samples used in this study were chosen to gain further knowledge of typical wood features, including defects, typically found in practice. The dielectric properties of the wood features were analyzed in terms of the important physical driving influences of frequency and moisture content. This database will be useful for future research and development as it expands the knowledge base of known properties of wood.

Knowledge of the magnitude of dielectric properties of wood features and the ability to model their physical behavior may potentially lead to being able to classify features. This is often a first step in automating wood processes, whether the objective is to maximize recovery, value, or other issues. Results from this research presented a simple "global" approach to such classification. Much more could be gained by extending to a local approach by including context such as for example, "neighborhood" information. However, further development and research will be necessary to fully exploit the technology. In this regard, the possible combination of other sensing technologies, such as optical and X-rays, with dielectric scanning may prove promising.

The success of this research depended on the development of the dielectric spectrometer. A natural material such as wood inherently poses many challenges to such instrumentation, not only due to natural variation but also due to the exceptional range of electrical properties exhibited by wood. A double resonant measurement approach was considered most suitable to meet the challenge, and thus formed the basis for the dielectric spectrometer developed in this research. Encouraging results from this research show that there is potential for this approach in automated wood scanning applications.

One conclusion shown is that the dielectric constant is perhaps more deterministic than the loss tangent as a means for distinguishing between wood features. This observation by itself has practical significance as it implies that a non-contact technology is possible. While a non-contact approach might be more practical it would impart resolution and stability requirements that would need further research.

Several aspects related to the dielectric properties of wood remain for future research. Foremost, there is a need for a model to account for the behavior of the dielectric properties as influenced by moisture and excitation frequency. This research considered only three excitation frequencies and three moisture levels, which are not sufficient for developing a model. Although there is evidence that the dielectric constant behavior is mostly linear, the modeling of loss tangent behavior would be much more challenging. Such a model would allow for more accurate feature discrimination. A model would further allow the use of multiple-frequency dielectric sensing methods that explore the complex interrelationship between moisture content and excitation frequency. This research has shown that the dielectric properties of different wood features can be measured with adequate accuracy for the development of such a comprehensive model.

There also is considerable interest in the behavior of wood dielectrics around or above the fiber saturation point. This research studied dielectric properties under tightly-controlled moisture conditions to obtain the best possible estimates of the absolute values for the dielectric constant and loss tangent. This research has indicated that good results are possible when working at higher moisture contents. The moisture content range around and above the fiber saturation point, however, is difficult to control without affecting the surface properties of the samples as some form of soaking or surface wetting is required. It would be possible to work with green samples in moisture desorption. However, the preliminary experiment showed serious problems with sample dimensional stability as the fiber saturation point was approached.

The concern about possible sampling bias due to the arbitrary choice of the size or severity subcategories needs to be addressed. These may be addressed in future studies by including actual feature size and shape descriptors instead of the arbitrary categories. This research has shown that the traditional analysis of variance methods are not generally useful for analyzing the effects of the main factors. This problem will even be more pronounced when additional feature descriptors of a variable nature are introduced. One possible method of analysis would be an analysis of covariance; however, the complex interaction between moisture content and excitation frequency would need to be resolved first.

Future scanning applications for the forest products industry may require research work on sensor fusion. It would be possible for instance to combine an optical sensing system with a dielectric sensing system. Optical systems are known to provide highly descriptive information. However, that often leads to confusing interpretations due to the amount of distractive information. A considerable amount of domain expertise often is required to resolve such confusion. A single or multiple frequency dielectric sensing system would not be sensitive to visual information, but would be sensitive to wood fiber structure, wood micro structure, and wood chemistry components. Information from these two kinds of sensing systems, together, may potentially resolve some problems. In other words, including further domain knowledge into a decision process may solve specific problems that presently exist. A knowledge-based approach may be considered for such an application. This research work provided part of such domain knowledge on wood features.

Moisture detection using RF techniques has been used in the forest products industry for years with various degrees of success. This research has shown various aspects related to the dielectric behavior of wood that might be useful for making improvements to RF moisture detectors. The effects that common wood defects have on the magnitudes of dielectric measurements are very important in this instance. For example, the dielectric constant of clearwood at 10% moisture content and 10 MHz is shown to be approximately 2.6, whereas large tight knots are shown to have a dielectric constant at the same moisture and frequency of approximately 4.3. In situations where an RF-based moisture detector is intended to measure clearwood but a large tight knot is encountered instead, the moisture detector would indicate a moisture content in excess of 20%. This situation occurs frequently with in-line moisture detectors. The same kind of error also occurs with in-kiln moisture detectors where the detector is effectively simultaneously exposed to a number of boards.

It may thus be concluded from this research that the dielectric properties of wood provide valuable insight into the structure of wood as well as its chemical composition. When using the appropriate technology, these findings may prove to be useful in several applications in the wood industry, some of which are already being exploited or improved. However, there remain a number of other potential applications to be researched and developed in the future.

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APPENDICES

APPENDIX 1: AN ANALYSIS OF THE DOUBLE RESONANT TECHNIQUE FOR THE MEASUREMENT OF DIELECTRIC PROPERTIES OF WOOD

An extension of the resonant method using a pair of resonant circuits to measure dielectric parameters of materials with high loss factor is described by Ichijo (1953). The device makes the indirect determination of dielectric constant and loss tangent possible by a method of substitution. The operation of the device as a single resonant circuit will be shown first. Figure A.1.1 shows a schematic for a single resonant circuit. An R.F. oscillator couples energy into a LC network consisting of a fixed inductance L1 that is brought to resonance to the oscillator frequency by variable capacitors C_v and C_d. The network composed of r, S_1, C_1 and C_2, is used for determination of loss factor. C_d is a differential capacitor consisting of C1 and C2. Regardless of the state of the rotor shaft, the nett capacitance of C_d remains constant. The purpose of S_1 is to enable various resistances to be switched in series with one half of the differential capacitor. The unknown capacitance and resistance are connected to the LC network in parallel. A diode detector is used to indicate resonance in the LC circuit.

The value of the unknown capacitor, C_x, is determined by closing S_1, thus eliminating the series resistor, r, and then bringing the LC circuit to resonance by varying C_v until a maximum is shown by the detector. Let this state be indicated by I_{g1} and C_{v1}. The circuit is again brought to resonance, this time without the unknown connected. Let this state correspond to I_{g2} and C_{v2}.

The value of the unknown capacitance is then given by:

$C_x = C_{v2} - C_{v1}$

The value of the unknown resistance R_x is determined by opening S_1 and tuning C_d until the detector indicates that same value as I_{g2}. The value of R_x is then given by:

$$R_x = \frac{1}{w^2 C_1^2 r}$$

where w = $2\pi f$ (f = frequency)
$C_1 = C_d$ from calibrated dial
r = series resistance in C_1 branch of C_d.

The error due to leakage resistance in the circuit is not taken into account in this form of the circuit. The derivation for R_x is as follows:

Converting a series RC network to an equivalent parallel R_pC_p network:

$$R_p = \frac{R_s^2 + X_s^2}{R_s^2} = \frac{r^2 + \frac{1}{(-wC)^2}}{r} \tag{1}$$

$$R_p = \frac{w^2C^2r^2+1}{w^2C^2r} \tag{2}$$

Assuming that the product $w \cdot C \cdot r < 0.1$ then $w^2C^2R^2 < 0.01$

thus:

$$Rp \approx \frac{0.01+1}{w^2C^2r} = \frac{1.01}{w^2C^2r} \approx \frac{1}{w^2C^2r} \tag{3}$$

A similar process is applied to find the equivalent parallel capacitance. Xp:

$$X_p = \frac{R_s^2+X_s^2}{X_s} = \frac{r^2+\frac{1}{(-wC)^2}}{\frac{1}{(-wC)}} \tag{4}$$

$$X_p = -\left(\frac{1}{wC}\right) - wCr^2 = \frac{1-w^2C^2r^2}{wC} \tag{5}$$

$$X_p \approx \frac{-1-0.01}{wC} = \frac{-1.01}{wC} \approx \frac{-1}{wC} \tag{6}$$

This means that the equivalent parallel capacitance is the same as for the series capacitance, or that the differential capacitor acts as a constant capacitance. Usage of the differential capacitor presents a constant capacitance regardless of the setting of the capacitor, i.e.

$$C_d = C_1 + C_2 = \text{Constant}$$

The use of the differential capacitor allows the introduction of a variable amount of parallel resistance across the circuit.

$R_p = 1 / (w^2C^2r)$ where the product, $w \cdot C \cdot r < 0.1$

Figure A.1.1 presents the Ichijo's double resonant approach of the circuit. In this case, C_v, the primary circuit variable capacitor does not need to be calibrated. The actual value of this capacitance is not needed. It merely serves as a means for adjusting the primary LC circuit to resonance. C_s, the variable capacitor in the secondary circuit, needs a calibrated dial as its value is required for the determination of C_x, the unknown capacitance.

Also note that the leakage resistance, due to internal component leakage, R_0, will be accounted for in this configuration. The difference between the single resonant circuit and the double resonant circuit is that the load now becomes a series-parallel network consisting of C_o-$(L//R_o//C_s//C_x//R_x)$. Switch S_3 transforms the load with respect to the primary circuit as either C_o, or C_o in series with a lumped reactance (formed by L,R_o,C_s,C_x,R_x). It will be shown how S_3 is used for the determination of R_x.

Another difference is that the adjustment of C_s will cause power to be drawn from the primary circuit resulting in a reduction in detector current. Resonance of the secondary circuit will be corresponding to a minimum in detector current.

Next, an equivalent parallel RC network representing the series-parallel network C_o-($L//R_o//C_s//C_x//R_x$) derived. This derivation will be shown in two steps.

Step 1:

The derivation of a series reactance-resistance network representing the parallel network L,R_o,C_s,C_v,R_x. If C represents the total capacitance, the component susceptances and total susceptance of the components are given by:

$$L = -1/(wL);\ G = 1/R_o;\ B_C = wC$$

$$B_{total} = -1/(wL) + wC = (wL \cdot wC - 1)/wL$$

The equivalent series resistance r_e is given by:

$$r_e=\frac{G}{G^2+B^2}=\frac{\frac{1}{R_o}}{\frac{1}{R_o^2}+(\frac{wLwC-1}{wL})^2}=\frac{\frac{1}{R_o}}{\frac{(wL)^2+R_o^2(1-wLwC)^2}{R_o^2(wL)^2}} \qquad (7)$$

$$r_e=\frac{R(wL)^2}{(wL)^2+R^2(1-w^2LC)}=\frac{\frac{(wL)^2}{R_o}}{(\frac{wL}{R_o})^2+(1-w^2LC)} \qquad (8)$$

The equivalent series reactance X_e is given by:

$$X_e=\frac{-B}{G^2+B^2}=\frac{-(wC-\frac{1}{wL})}{\frac{1}{R_o^2}+(wC-\frac{1}{wL})^2} \qquad (9)$$

$$X_e=\frac{-(\frac{w^2LC-1}{wL})}{\frac{(wL)^2+R^2(w^2LC-1)^2}{R^2(wL)^2}}=\frac{-(w^2LC-1)R^2(wL)^2}{(wL)^2+R^2(w^2LC-1)} \qquad (10)$$

$$X_e=\frac{-(\frac{w^2LC-1}{wL})(wL)^2}{\frac{(wL)^2}{R^2}+(w^2LC-1)^2} \qquad (11)$$

Since

$$X_e = wL = \frac{wL(1-w^2LC)}{\frac{(wL)^2}{R^2} + (1-w^2LC)^2} \tag{12}$$

$$L_e = \frac{L(1-w^2LC)}{\frac{(wL)^2}{R^2} + (1-w^2LC)^2} \tag{13}$$

Step 2:

The derivation of an equivalent parallel resistance//reactance network representing the series r_e-L_e network. Since

$$X_{total} = X_L + X_C = wL_e - \frac{1}{wC_o} \tag{14}$$

$$G = \frac{R}{R^2+X^2} = \frac{1}{R_p} \tag{15}$$

$$R_p = \frac{r_e^2 + (wL_e - \frac{1}{wC_o})^2}{r_e} = r_e + \frac{(wLe - \frac{1}{wC_o})^2}{re} \tag{16}$$

Let $R_p = A + B$

Substituting for r_e:

$$A=\frac{\frac{w^2L^2}{R}}{\frac{w^2L^2}{R^2}+(1-w^2LC)^2}=\frac{w^2L^2R}{w^2L^2+R^2(1-w^2LC)^2} \tag{17}$$

$$B=\frac{(wL_e-\frac{1}{wC_o})^2}{r_e}=\frac{(w^2C_oL_e-1)^2}{w^2C_o^2r_e} \tag{18}$$

$$B=\frac{[\frac{w^2C_oL(1-w^2LC)}{(1-w^2LC)^2+\frac{w^2L^2}{R^2}}-1]^2}{w^2C_o^2r_e} \tag{19}$$

$$B=\frac{[\frac{w^2C_oLR^2(1-w^2LC)}{w^2L^2+R^2(1-w^2LC)^2}-1]^2}{w^2C_o^2r_e} \tag{20}$$

$$B=\frac{[w^2C_oLR^2(1-w^2LC)-(w^2L^2+R^2(1-w^2LC)^2)]^2}{[w^2C_o^2r_e(w^2L^2+R^2(1-w^2LC)^2]^2} \tag{21}$$

$$B=\frac{[R^2(1-w^2LC)(w^2C_oL-(1-w^2LC))-w^2L^2]^2}{[w^2C_o^2r_e(w^2L^2+R^2(1-w^2LC)^2]^2} \tag{22}$$

$$B=\frac{[R^2(1-w^2LC)(w^2L(C_o+C)-1)-w^2L^2]^2}{[w^2C_o^2r_e(w^2L^2+R^2(1-w^2LC)^2]^2} \tag{23}$$

$$B=\frac{[R^2(1-w^2LC)(1-w^2L(C_o+C)+w^2L^2]^2}{[w^2C_o^2r_e(w^2L^2+R^2(1-w^2LC)^2]^2} \tag{24}$$

$$B=\frac{[R^2(1-w^2LC)(1-w^2L(C_o+C))+w^2L^2]^2}{\dfrac{w^2C_o^2(w^2L^2+R^2(1-w^2LC)^2)^2w^2L^2}{R((1-w^2LC)^2+\dfrac{w^2L^2}{R^2})}} \tag{25}$$

$$B=\frac{[R^2(1-w^2LC)(1-w^2L(C_o+C))+w^2L^2]^2}{\dfrac{w^4C_o^2L^2R[w^2L^2+R^2(1-w^2LC)^2]^2}{R^2(1-w^2LC)^2+w^2L^2}} \tag{26}$$

$$B=\frac{[R^2(1-w^2LC)(1-w^2L(C_o+C))+w^2L^2]^2}{w^4C_o^2L^2R[w^2L^2+R^2(1-w^2LC)^2]} \tag{27}$$

The equivalent parallel capacitance C_p is found using a similar derivation:

$$B_c=wC_p=\frac{-X}{R^2+X^2}=\frac{-(wL_e-\dfrac{1}{wC_o})}{r_e^2+(wL_e-\dfrac{1}{wC_o})^2} \tag{28}$$

$$B_c=\frac{-(w^2L_eC_o-1)}{wC_o(r_e^2+(wL_e-\dfrac{1}{wC_o})^2} \tag{29}$$

$$B_c=\frac{1-w^2L_eC_o}{wC_o(r_e^2+(\dfrac{w^2L_eC_o-1}{wC_o})^2} \tag{30}$$

$$B_c = \frac{1 - w^2 L_e C_o}{\frac{wC_o(w^2 C_o^2 r_e^2 + (w^2 L_e C_o - 1)^2)}{(wC_o)^2}} \tag{31}$$

$$B_c = \frac{wC_o(1 - w^2 L_e C_o)}{w^2 C_o^2 r_e^2 + (w^2 L_e C_o - 1)^2} \tag{32}$$

L_e is now substituted in the numerator:

$$B_c = \frac{wC_o\left(1 - \frac{w^2 L C_o (1 - w^2 LC)}{(1 - w^2 LC)^2 + \frac{w^2 L^2}{R^2}}\right)}{w^2 C_o^2 r_e^2 + (w^2 L_e C_o - 1)^2} \tag{33}$$

$$B_c = \frac{wC_o\left(1 - \frac{w^2 R^2 L C_o (1 - w^2 LC)}{R^2 (1 - w^2 LC)^2 + w^2 L^2}\right.}{w^2 C_o^2 r_e^2 + (w^2 L_e C_o - 1)^2} \tag{34}$$

$$B_c = \frac{wC_o(R^2(1 - w^2 LC)^2 + w^2 L^2 - w^2 R^2 L C_o (1 - w^2 LC)}{(R^2(1 - w^2 LC)^2 + w^2 L^2)\,[w^2 C_o^2 r_e^2 + (w^2 L_e C_o - 1)^2]} \tag{35}$$

$$B_c = \frac{wC_o[R^2(1 - w^2 LC)((1 - w^2 LC) - w^2 L C_o) + w^2 L^2]}{(R^2(1 - w^2 LC)^2 + w^2 L^2)((w^2 C_o^2 r_e^2) + (w^2 L_e C_o - 1)^2)} \tag{36}$$

$$B_c = \frac{wC_o[R^2(1 - w^2 LC)(1 - w^2 L(C + C_o)) + w^2 L^2]}{(R^2(1 - w^2 LC)^2 + w^2 L^2)[(w^2 C_o^2 r_e^2) + (w^2 L_e C_o - 1)^2]} \tag{37}$$

L_e and r_e is now substituted in the denominator:

$$B_c=\frac{wC_o[R^2(1-w^2LC)(1-w^2L(C+C_o))+w^2L^2]}{(R^2(1-w^2LC)^2+w^2L^2)(w^2C_o^2[\frac{w^2L^2}{R(1-w^2LC)^2+\frac{w^2L^2}{R^2}}]^2+\ldots}$$

$$\ldots[\frac{w^2C_oL(1-w^2LC)}{(1-w^2LC)^2+\frac{w^2L^2}{R^2}}-1]^2 \qquad (38)$$

$$B_c=\frac{wC_o(R^2(1-w^2LC)(1-w^2L(C+C_o))+w^2L^2)}{(R^2(1-w^2LC)^2+w^2L^2)(w^2C_o^2[\frac{Rw^2L^2}{R^2(1-w^2LC)^2+w^2L^2}]^2+\ldots}$$

$$\ldots[\frac{R^2w^2C_oL(1-w^2LC)}{R^2(1-w^2LC)^2+w^2L^2}-1]^2 \qquad (39)$$

$$B_c=\frac{(R^2(1-w^2LC)^2+w^2L^2)[wC_o(R^2(1-w^2LC)(1-w^2L(C+C_o))+w^2L^2)]}{w^2C_o^2(R^2L^2)^2+[R^2w^2C_oL(1-w^2LC)-(R^2(1-w^2LC)^2+w^2L^2)]^2}$$

$$B_c=\frac{(R^2(1-w^2LC)^2+w^2L^2)[wC_o(R^2(1-w^2LC)(1-w^2L(C+C_o))+w^2L^2)]}{w^2C_o^2(R^2L^2)^2+[R^2(1-w^2LC)(w^2C_oL-(1-w^2LC))-w^2L^2]^2}$$

$$B_c=\frac{(R^2(1-w^2LC)^2+w^2L^2)\,[wC_o(R^2(1-w^2LC)(1-w^2L(C+C_o))+w^2L^2)]}{w^2C_o^2(R^2L^2)^2+[R^2(1-w^2LC)(w^2L(C_o+C)-1)-w^2L^2]^2}$$

$$B_c=\frac{(R^2(1-w^2LC)^2+w^2L^2)\,[wC_o(R^2(1-w^2LC)(1-w^2L(C+C_o))+w^2L^2)]}{w^6L^4C_o^2+[R^2(1-w^2LC)(1-w^2L(C_o+C)+w^2L^2)]^2}$$

Divide both nominator and denominator by R^4:

$$B_c=\frac{((1-w^2LC)^2+\frac{w^2L^2}{R^2})\,(w^2C_o(1-w^2LC)(1-w^2L(C+C_o))+\frac{w^2L^2}{R^2})}{\frac{w^6L^4C_o^2}{R^2}+[(1-w^2LC)(1-w^2L(C+C_o)+\frac{w^2L^2}{R^2})]^2} \qquad (44)$$

Divide both numerator and denominator by:

$$[(1-w^2LC)(1-w^2L(C+C_o)+\frac{w^2L^2}{R^2})]^2$$

Then:

$$B_c=\frac{wC_o((1-w^2LC)^2+\frac{w^2L^2}{R^2})}{(1-w^2LC)(1-w^2L(C+C_o)+\frac{w^2L^2}{R^2})}x$$

$$\frac{1}{1+\frac{\frac{w^6L^4C_o^2}{R^2}}{[(1-w^2LC)(1-w^2L(C+C_o)+\frac{w^2L^2}{R^2})]^2}} \tag{45}$$

Since $B_c = wC_p$, it follows that:

$$C_p=\frac{C_o((1-w^2LC)^2+\frac{w^2L^2}{R^2})}{(1-w^2LC)(1-w^2L(C+C_o)+\frac{w^2L^2}{R^2})}x$$

$$\frac{1}{1+\frac{\frac{w^6L^4C_o^2}{R^2}}{[(1-w^2LC)(1-w^2L(C+C_o)+\frac{w^2L^2}{R^2})]^2}} \tag{46}$$

The response of C_p and R_p as a function of C are shown in Figure A.1.2. Since R_p represents the load resistance presented to the primary tuned circuit, R_p, will determine the value of I_g. I_g will be a minimum when R_p is minimum. Ichijo showed that this minimum occurred when:

$$C=\frac{1-w^2LC_0}{w^2L} \tag{47a}$$

This result is confirmed by finding a graphical solution for this minimum value of R_p, i.e. d(Rp)/dC = 0. For the example shown in Figure A.1.2, this corresponds to where:

$$C=71.52=73.0-1.48pF=C_r-C_0 \tag{47b}$$

$$C=C_r-C_0=\frac{1}{w^2L}-C_0 \tag{47c}$$

$$C=\frac{1-w^2LC_o}{w^2L} \tag{48}$$

Note that in Figure A.1.2 that the value of C for minimum Ig is independent of R. R, however, does influence the shape of the curve. This very important observation is the basis for separating the real and imaginary parts of the dielectric constant, i.e. conduction and capacitive admittance. Also note that on Figure A.1.2 that lower values of R produce nearly flat resonance curves that makes judgement of the true minimum value, as indicated by I_g, extremely difficult for manual operation. The device used in this study uses an A/D convertor and a software peak detector for this purpose. The values of Rp and Cp when Ig is minimum are found by substituting (48) into (17),(18) and (46):

$$R_p=\frac{w^2L^2R}{R^2(w^2LC_o)^2+w^2L^2}+\frac{(w^2L^2)^2}{w^4L^2C_o^2R[R^2(w^2LC_o)^2+w^2L^2]} \tag{49}$$

$$R_p=\frac{w^2L^2R(w^4L^2C_o^2R)+(w^2L^2)^2}{w^4L^2C_o^2R[R^2(w^2LC_o)^2+w^2L^2]} \tag{50}$$

$$R_p=\frac{R^2(w^2LC_o)^2+w^2L^2}{w^2C_o^2R[R^2(w^2LC_o)^2+w^2L^2]}=\frac{1}{w^2C_o^2R} \tag{51}$$

Similarly:

$$C_p=\frac{C_o((w^2LC_o)^2+\frac{w^2L^2}{R^2}}{\frac{w^2L^2}{R^2}}x\frac{1}{1+\frac{w^6L^4C_o^2}{R^2(\frac{w^2L^2}{R^2})^2}} \tag{52}$$

$$C_p=\frac{C_o((w^2LC_o)^2+\frac{w^2L^2}{R^2})}{\frac{w^2L^2}{R^2}}x\frac{\frac{(w^2L^2)^2}{R^2}}{(\frac{w^2L^2}{R^2})^2+\frac{w^6L^4C_o^2}{R^2}} \tag{53}$$

$$C_p=C_o((w^2LC_o)^2+\frac{w^2L^2}{R^2})x\frac{\frac{w^2L^2}{R^2}}{\frac{w^2L^2}{R^2}[\frac{w^2L^2}{R^2}+\frac{(w^2LC_o)^2}{R^2}]}=C_o \tag{54}$$

To compensate for the leakage resistance, Ro, Rx may be derived from the expression of parallel resistances:

$$\frac{1}{R_p}=\frac{1}{R_x}+\frac{1}{R_o}$$

Thus

$$R_x=\frac{R_pR_o}{R_p+R_o}$$

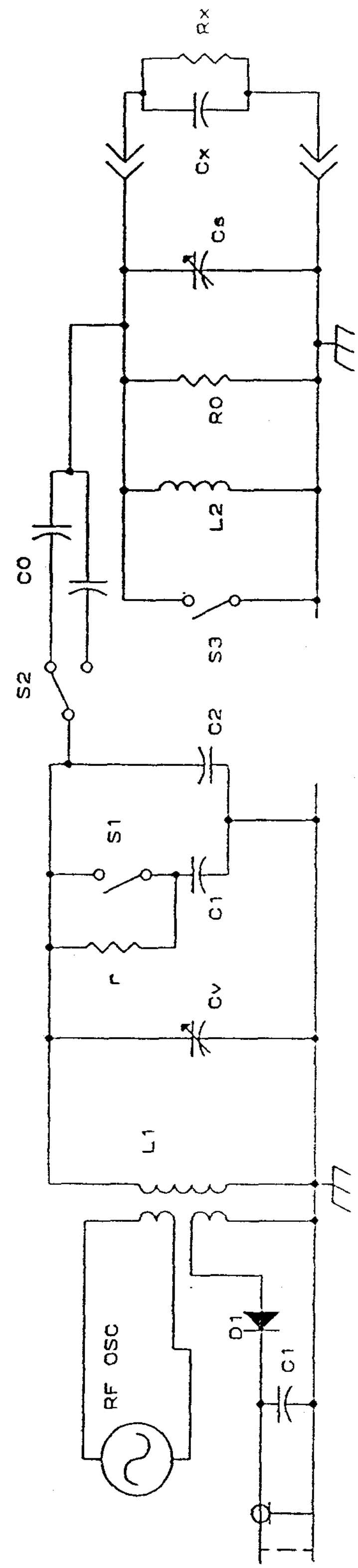

Figure A.1.1. Schematic for Ichijo's (1953) device for measuring the dielectric constant and loss factor of materials with high loss factors.

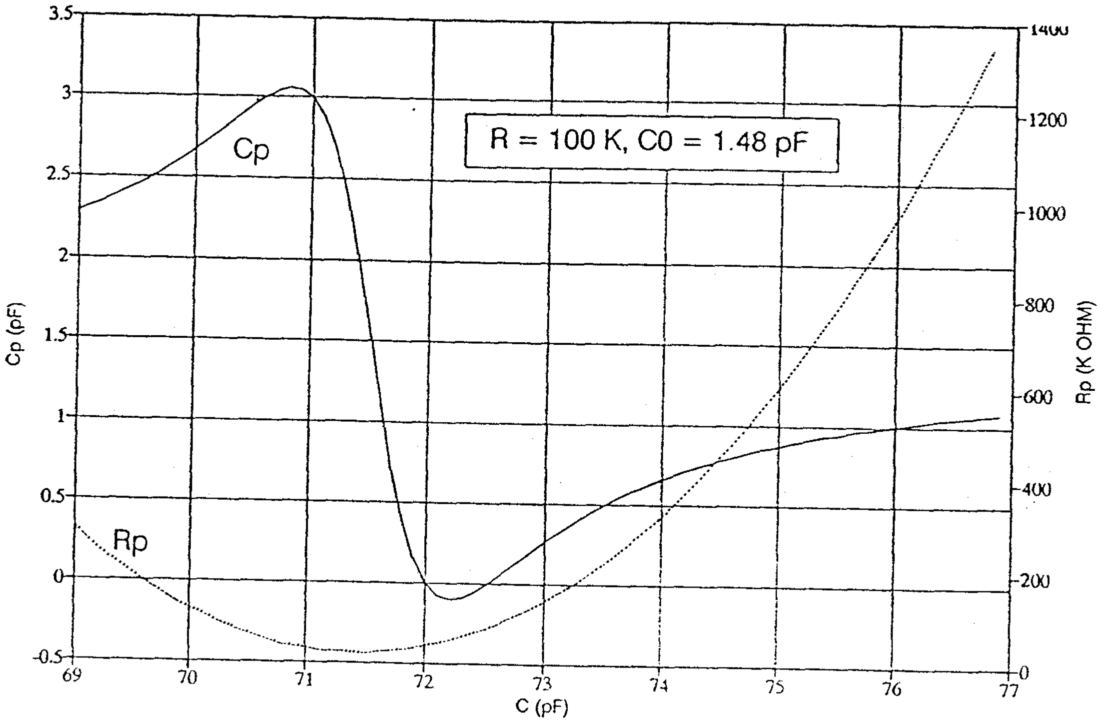

Figure A.1.2. The response of C_p and R_p as a function of C.

APPENDIX 2: DIELECTRIC SPECTROMETER CALIBRATION AND REPEATABILITY EVALUATION

A.2.1. Calibration of Dielectric Constant

The device has been calibrated for fine capacitance resolution for the range of test frequencies 1.4, 4, 10, 20, and 49 MHz. A test set of ceramic capacitors covering the range 1 to 10 pF is used for this purpose. These calibration capacitors are low cost 10% tolerance components. It is expected that these calibration components will exhibit random +/- tolerances. A regression equation of shaft encoder voltage on capacitance was then determined for each frequency. These calibration equations are shown in Table A.2.1. The following procedure is performed for each of the test frequencies:

Step 1. Install the appropriate plug-in LC module. Fully extend the electrode gap to approximately 0.75 inches. This effectively eliminates between-electrode capacitance, leaving only residual capacitance, i.e., stray capacitances and guard capacitance. Rotate the fine tuning capacitance to its maximum capacitance value, i.e., the capacitor plates fully meshed. A special mechanical stop has been added to give a positive reference position.

Step 2. Enable SW3. This short-circuits the secondary LC measurement circuit, however, includes the series-coupling capacitor, C_0 (Figure A.1.1). Tune the primary tuning capacitor for maximum drive. This corresponds to a relatively sharp increase in output from the detector as indicated on the panel meter.

Step 3. Open SW3 to engage the secondary LC measurement circuit. Tune the coarse tuning capacitor for minimum output as indicated on the panel meter. This indicates that resonance has been achieved in the test LC circuit. This setting corresponds to "ZERO" capacitance.

Step 4. Start the calibration program: DIEL. This is a data acquisition program that selects resonance peaks and records the corresponding position of the shaft encoder. Subsequent conversion of shaft encoder values to actual capacitance values is then possible using the appropriate calibration equation. Proceed to obtain a reading for resonance for each of the test capacitors. The final results of the calibration procedure are saved in a disk file for further analysis. Final calibration equations obtained for 1.4, 4, 10, and 49 MHz is shown in Table A.2.1.

Table A.2.1. Calibration equations for 1.4, 4, 10, 20, and 49 MHz. "E" is measured encoder output in Volts.

Frequency	Equation (pF)	Correlation
1.4 MHz	7.3961-2.1445.E	0.9952
4.0 MHz	7.3666-2.1278.E	0.9946
10.0 MHz	7.8434-2.2903.E	0.9962
20.0 MHz	7.6292-2.2214.E	0.9954
49.0 MHz	8.0553-2.2971.E	0.9901

The calibration equations shows minor differences in the constant term. This shows the ability to accurately reset the coarse tuning capacitor. However, since this resettability adjustment affects only the constant term of the calibration equation, actual absolute capacitance may be found by using a known material as a test dielectric at the start of each experiment.

A.2.2 Calibration for Loss Factor

Accurate measurement of the loss factor for wood is a difficult undertaking due to the extreme range of conductance of wood from in its green to its dry state. One of the main reasons why most research deals with wood in its dry state, or wood at moisture content below fiber saturation, is due to the dominant effect that moisture content has on dielectric measurements is. This problem was reported both by Peterson (1960) and James (1975) when dealing with higher moisture content samples, however neither suggested an alternate solution.

Some practical constraints need to be observed when using Ichijo's design for the measurement of loss factor. Ichijo showed that the equations for the calculation of loss factor may be substantially simplified when certain product terms are small fractions, i.e.,

$$2\pi fCR < 0.1$$

where: f is the measurement frequency
C is the value of substituted capacitance
R is the amount for substituted series resistance.

For a given fixed resistance, r (Figure A.1.1), i.e., 499 Ohm in our case, this amounts the following substitution capacitances:

Table A.2.2. Capacitance values to satisfy $2\pi fCR < 0.1$

Frequency MHz	Capacitance pF
1.4	22.78
4.0	7.79
10.0	3.19
20.0	1.59
49.0	0.64

Table A.2.2 shows that this method would not be practicable above 4 MHz due to the device's internal stray capacitances and imperfection in the split-stator capacitor. This has also been found to be the case in practice.

As an alternate measurement of loss factor, a Q-based method is suggested. The Q method, in the case for a fixed excitation frequency, is based on the ratio:

Q = Er/Es, where Er = the voltage rise at resonance,
and
Es = the excitation voltage.

Table A.2.3 tabulates results from an experiment using a range of known load resistances that uses such a Q-based measurement as compared to results obtained from Ichijo's substitution method. 1.4 MHz was used for this comparison as it represents the higher useful range for Ichijo's method.

Table A.2.3. Ichijo's substitution method and effective "Q" measurements at a frequency of 1.4 MHz using a series of 5% carbon composition resistors as reference. The column "Test R" should be compared with "Reff." The values shown with "*" are cases where the relation $2\pi fRC < 0.1$ is not valid.

Test R Ohm	Cres. pF	D meas	Csubst pF	$2\pi fRC$	Rtot	Reff Ohm	Deff Ohm
10M	0.87	2.26	37.0	0.162*	75903	2.86M	0.004
1M	0.73	2.19	35.5	0.156*	69874	673K	0.017
560K	0.72	2.11	34.4	0.151*	65993	429.6K	0.026
330K	0.71	1.98	32.5	0.143*	58563	235.3K	0.048
100K	0.77	1.62	26.5	0.116*	38936	77.8K	0.146
22K	0.20	1.19	15.5	0.068	13321	16.1K	0.706

The availability of a range of different calibration standards for loss factor is more of a problem than for dielectric constant. NIST (Anon., 1991), lists two dielectric calibration standards:

silica: $\epsilon' + j\epsilon'' = 3.82 - j0.0005$ or
$\epsilon' = 3.82$ and $\tan\delta = \epsilon''/\epsilon' = 0.0005/3.82$

glass: $\epsilon' + j\epsilon'' = 6.20 - j0.0330$ or
$\epsilon' = 6.20$ and $\tan\delta = \epsilon''/\epsilon' = 0.033/6.20$

Considering the relationship $\tan\delta = 1/(2\pi fRC)$, sensor geometry (1pF air gap), and ϵ', conductance (1/R) can be calculated. For the above two standards, and our sensor set for approximately 1/8" gap, for a measurement frequency of 1.4 MHz:

conductance for silica $= 2\pi(1.4\text{ MHz})(3.82\text{pF})(0.0005)/3.82$
$= 4.3982297\text{e-}9\text{ S} = 0.0000043982297\ \mu\text{S}$

conductance for glass $= 2\pi(1.4\text{ MHz})(6.20\text{pF})(0.033)/6.2$
$= 2.9028316\text{e-}7\text{ S} = 0.29028316\ \mu\text{S}$

It is unfortunate that these conductance values are similar to that of very dry wood and thus not very useful for calibrating for the expected range for wood. For this reason the method using simulated load resistances, as described above was used for loss factor calibration purposes.

A.2.3 Dielectric Spectrometer Evaluation: Repeatability of Results Using a Test Material with Known Characteristics

A 7.5 x 8 x 1/8" rectangle of polyacrylite material (plexiglas) manufactured by Rohm and Haas was tested. This material is homogeneous and is thus ideally suited for verification of repeatability. According to the Handbook of Chemistry and Physics (Weast et al., 1989), this material has a listed dielectric constant of 2.76 at 1 MHz.

A reference grid made up of tiles measuring one inch on the sides was marked on the test sheet. The dielectric parameters of one row of the test sheet were then measured at its seven grid intersections in the lengthwise direction. At each of the seven locations on the sheet, five readings were taken. The SAS statistical analysis program ANOVA procedure was used to analyze this data set for accuracy and variability.

The overall mean for dielectric constant at 1.4 MHz was found to correspond to 2.71 +/- .0022 (at the 95% confidence level, measured at room temperature) that compared favorably to the CRC value of 2.76 - within 1.8% of the listed value. At 10 MHz the mean is within 0.33% and at 20 MHz the mean is within 0.79%.

The ANOVA's for dielectric constant and loss tangent is shown in Tables A.2.4 and A.2.7 respectively. Evidence of differences between locations is evident in both cases. Further testing of differences using Duncan's multiple range tests by frequency and location for dielectric constant are summarized in Tables A2.5 and A2.6. These reflect statistically significant differences between all the frequencies. On location, however, there appears to be little distinction between the group of locations 2 to 6, and the two extreme locations 1 and 7. The multiple range tests for loss tangent is summarized in Tables A.2.8 and A.2.9. The means for loss tangent shows that there is a statistical difference between 1.4 MHz and 10/20 MHz. There is no detectable difference between 10 and 20 MHz. The differences between locations for loss tangent follows a similar pattern to that for dielectric constant.

The conclusion that may be drawn from these results is as follows:

1. Dielectric constant and loss tangent shows similar behavior for frequency and location.

2. The repeatability by frequency suggests that the constant terms for the linear calibration equations may be slightly off calibration.

3. The observation that locations 1 and 7 behaves similarly for dielectric constant and loss tangent suggests that there be some mechanical cause and effect, i.e., how the sample is supported at the extreme ends are different to when measurements are taken from the middle part of the test sample.

4. The dielectric spectrometer is capable of repeatable and accurate measurements if the calibration step could be performed with good consistency.

Table A.2.4. Analysis of Variance for Dielectric Constant.

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	20	0.54357905	0.02717895	12.24	0.0001
Error	84	0.18656000	0.00222095		
Total	104	0.73013905			

Source	DF	Anova SS	Mean Square	F Value	Pr > F
FREQ	2	0.06915048	0.03457524	15.57	0.0001
LOC	6	0.42227238	0.07037873	31.69	0.0001
FREQ* LOC	12	0.05215619	0.00434635	1.96	0.0387

Table A.2.5. Duncan's Multiple Range Test for Dielectric Constant by frequency. NOTE: This test controls the type I comparisonwise error rate, not the experimentwise error rate. Alpha= 0.05 df= 84 MSE= 0.001848. Critical Range 0.02240, 0.02357.

Duncan Grouping	Mean	N	FREQ
A	2.76914	35	10
B	2.73829	35	20
C	2.70629	35	1

Table A.2.6. Duncan's Multiple Range Test for Dielectric Constant by location. NOTE: This test controls the type I comparisonwise error rate, not the experimentwise error rate. Alpha= 0.05 df= 84 MSE= 0.001848. Critical Range 0.03422, 0.03601, 0.03719, 0.03806, 0.03873, 0.03927.

Duncan Grouping		Mean	N	FREQ
	A	2.79533	15	3
	A	2.78800	15	4
B	A	2.78267	15	6
B	A	2.76000	15	2
B		2.75067	15	5
	C	2.67733	15	7
	D	2.61133	15	1

Table A.2.7. Analysis of Variance for Loss Tangent.

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	20	0.00091665	0.00004583	11.00	0.0001
Error	84	0.00034984	0.00000416		
Total	104	0.00126649			
Source	DF	Anova SS	Mean Square	F Value	Pr > F
FREQ	2	0.00041394	0.00020697	49.69	0.0001
LOC	6	0.00025864	0.00004311	10.35	0.0001
FREQ* LOC	12	0.00024407	0.00002034	4.88	0.0001

Table A.2.8. Duncan's Multiple Range Test for Loss Tangent. NOTE: This test controls the type I comparisonwise error rate, not the experimentwise error rate. Alpha= 0.05 df= 84 MSE= 4.165E-6. Critical Range 0.000970, 0.001021.

Duncan Grouping	Mean	N	FREQ
A	0.0203086	35	10
A	0.0202343	35	20
B	0.0160600	35	1

Table A.2.9. Duncan's Multiple Range Test for Loss Tangent. NOTE: This test controls the type I comparisonwise error rate, not the experimentwise error rate. Alpha= 0.05 df= 84 MSE= 4.165E-6. Critical Range 0.001482, 0.001559, 0.001611, 0.001648, 0.001677, 0.001701.

Duncan Grouping	Mean	N	FREQ
A	0.0203467	15	4
A	0.0201067	15	3
A	0.0196867	15	6
A	0.0195867	15	2
A	0.0192867	15	5
B	0.0173133	15	1
C	0.0157467	15	7

APPENDIX 3: PRELIMINARY EXPERIMENT: RELATIONSHIP BETWEEN MOISTURE CONTENT AND FREQUENCY FOR WOOD FEATURES.

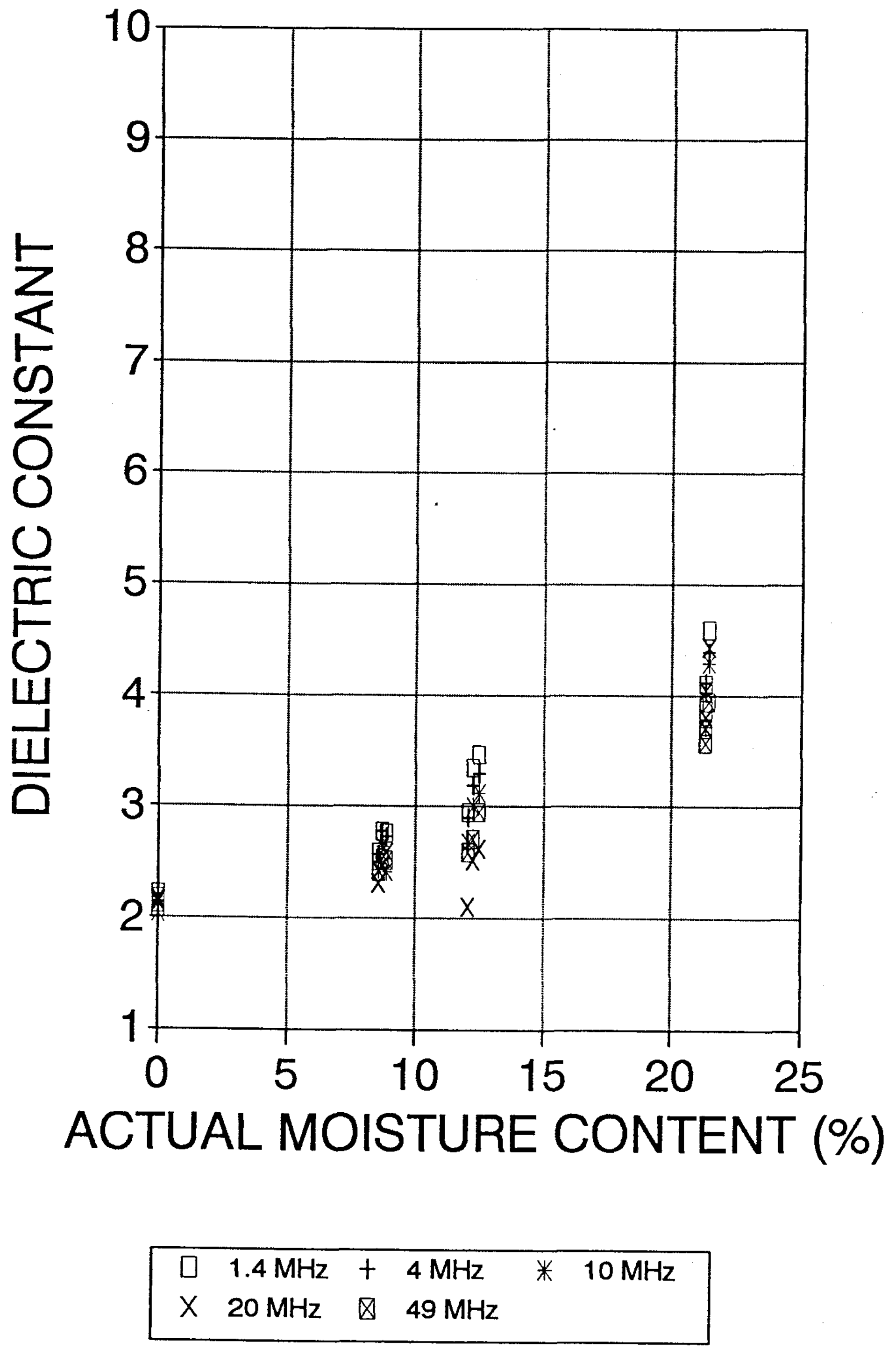

Figure A.3.1. Effect of moisture content on dielectric constant for clear heartwood.

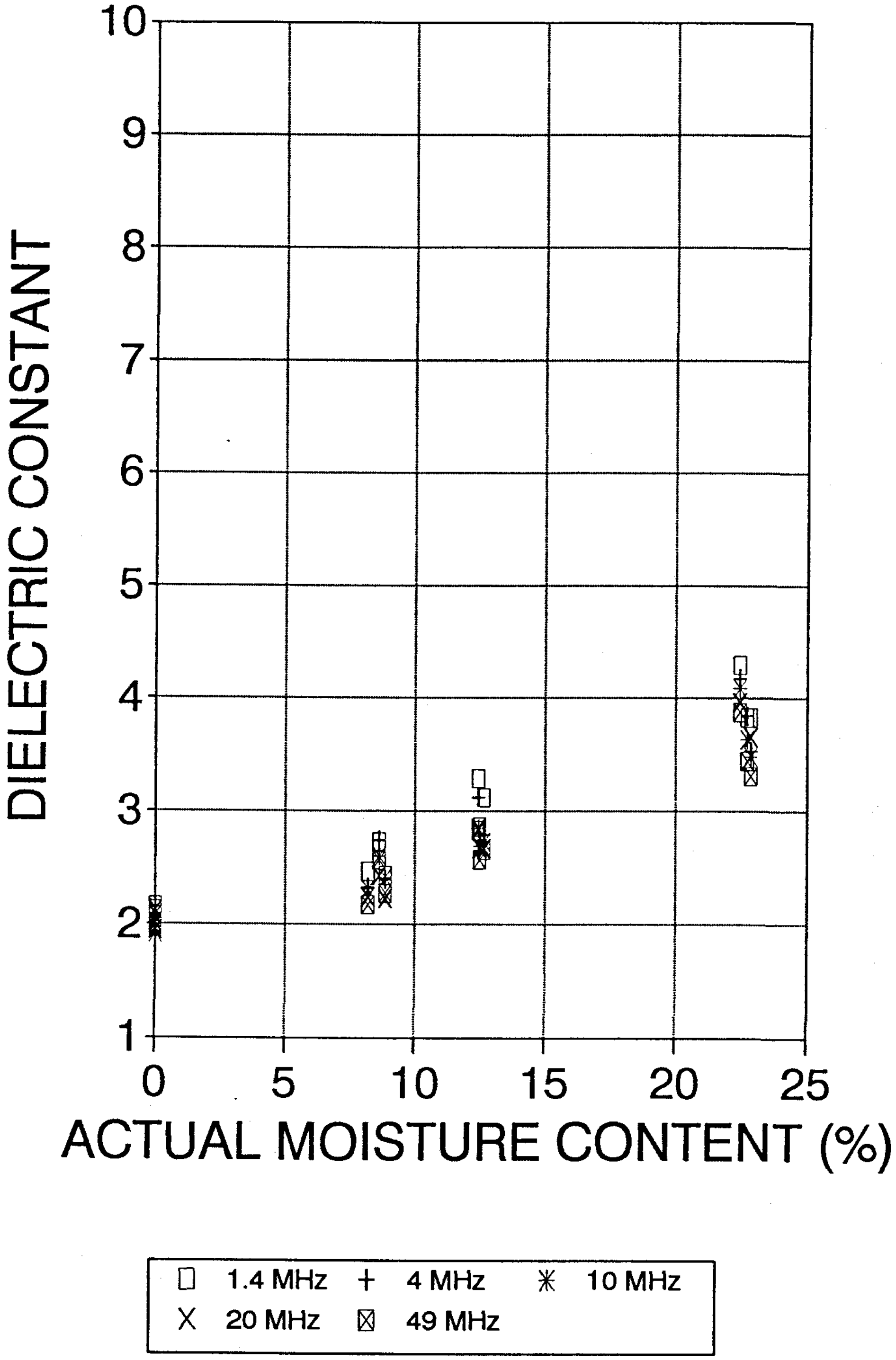

Figure A.3.2. Effect of moisture content on dielectric constant for clear sapwood.

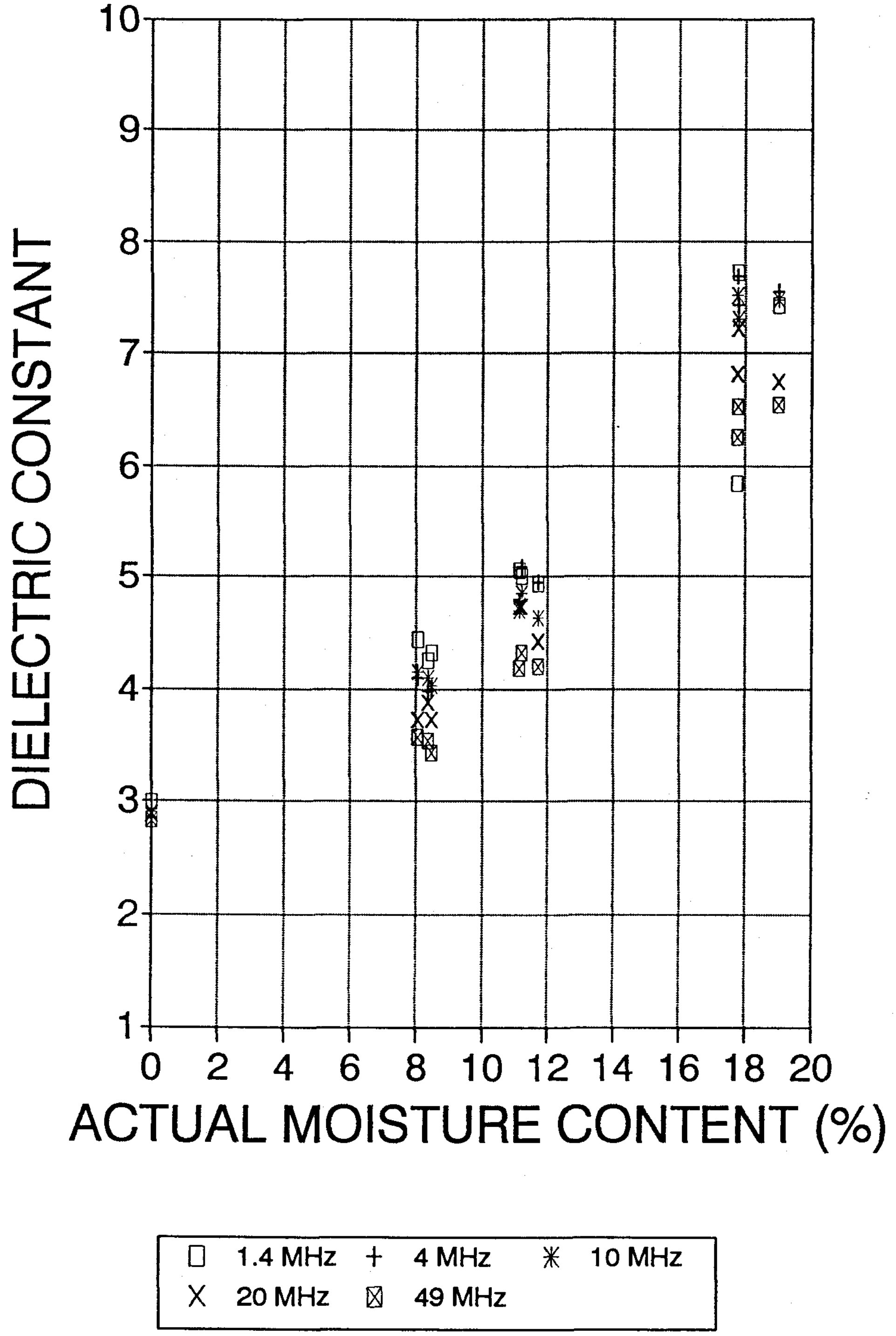

Figure A.3.3. Effect of moisture content on dielectric constant for large tight knots.

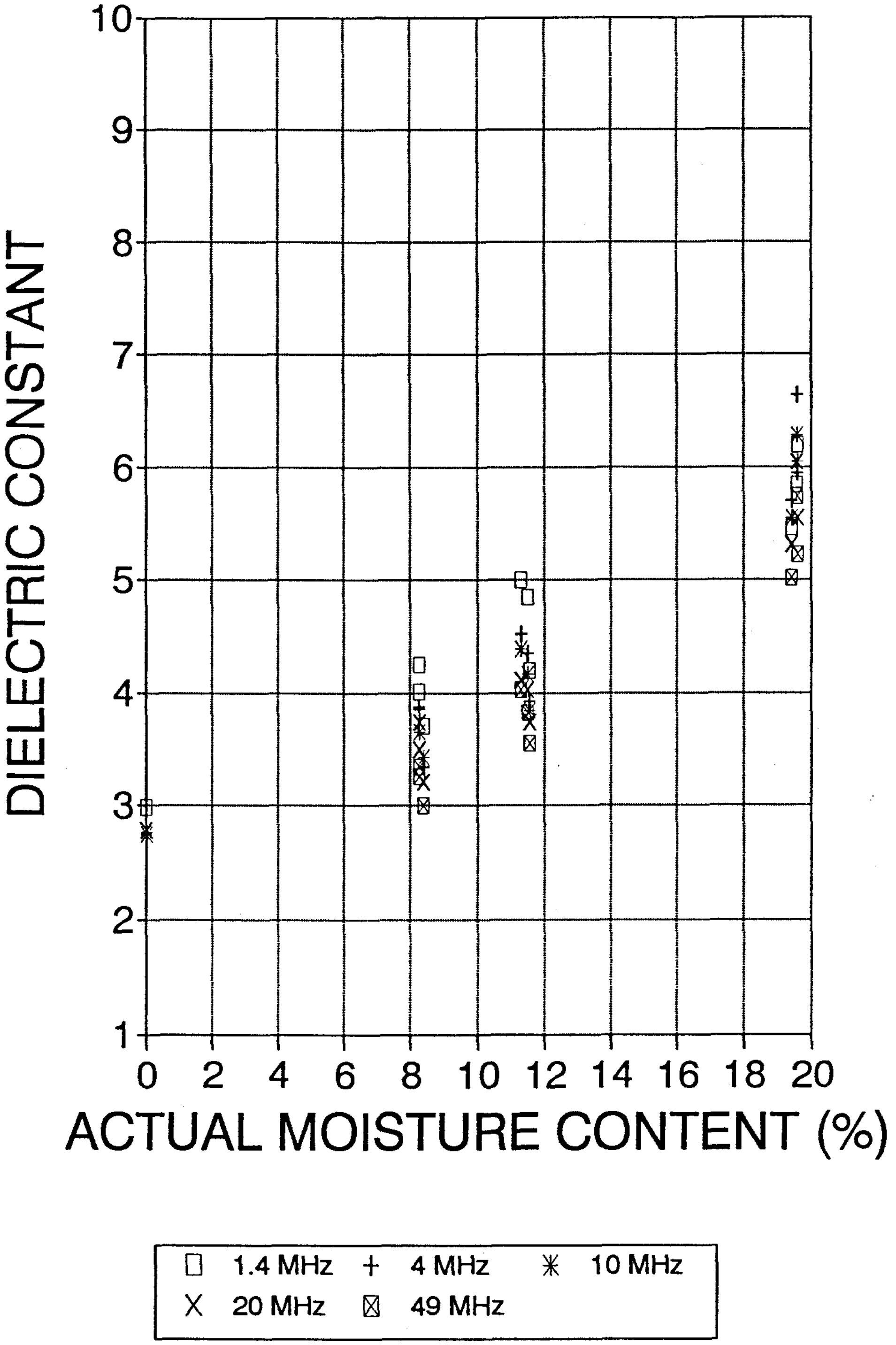

Figure A.3.4. Effect of moisture content on dielectric constant for medium tight knots.

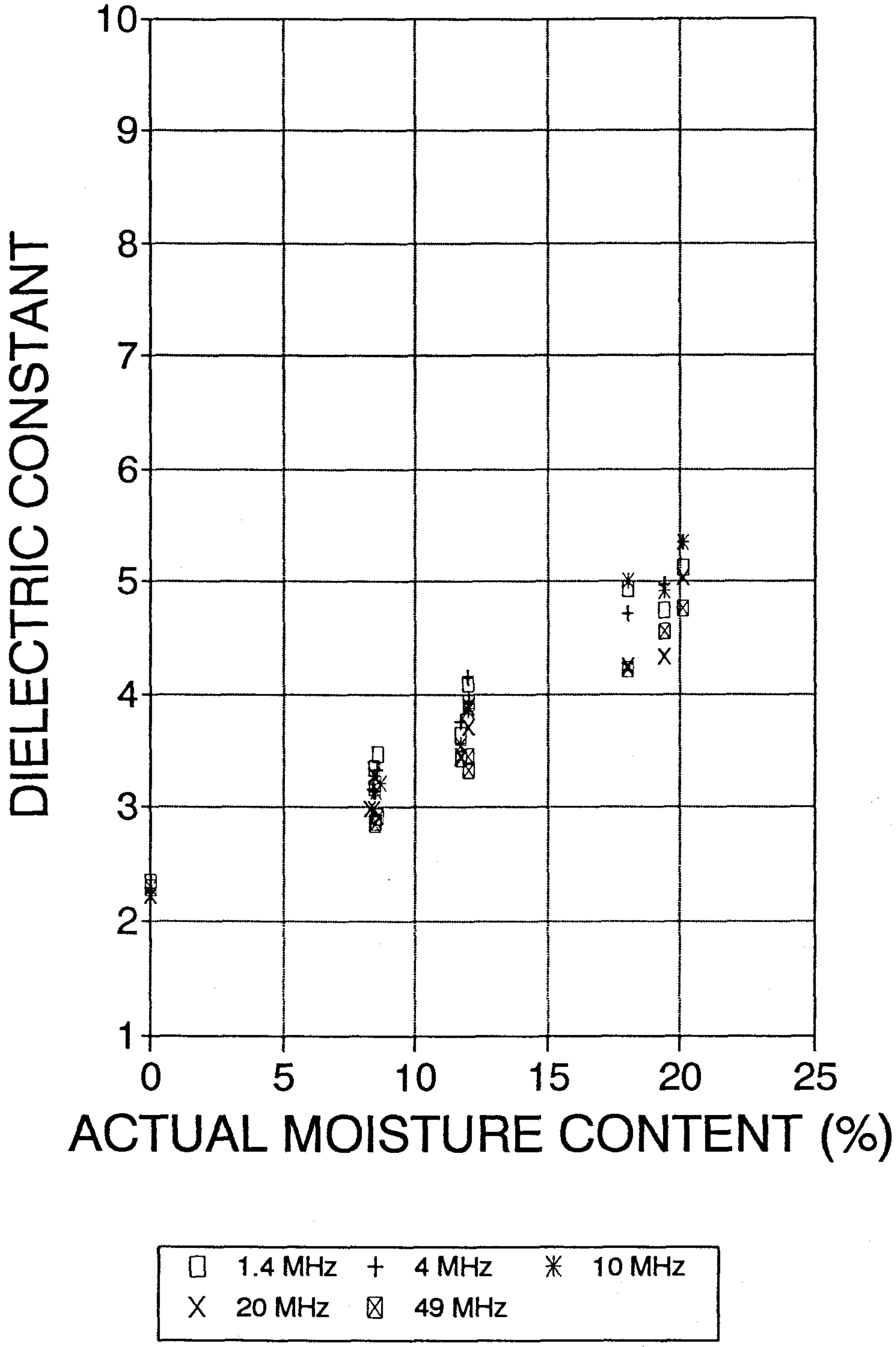

Figure A.3.5. Effect of moisture content on dielectric constant for small tight knots.

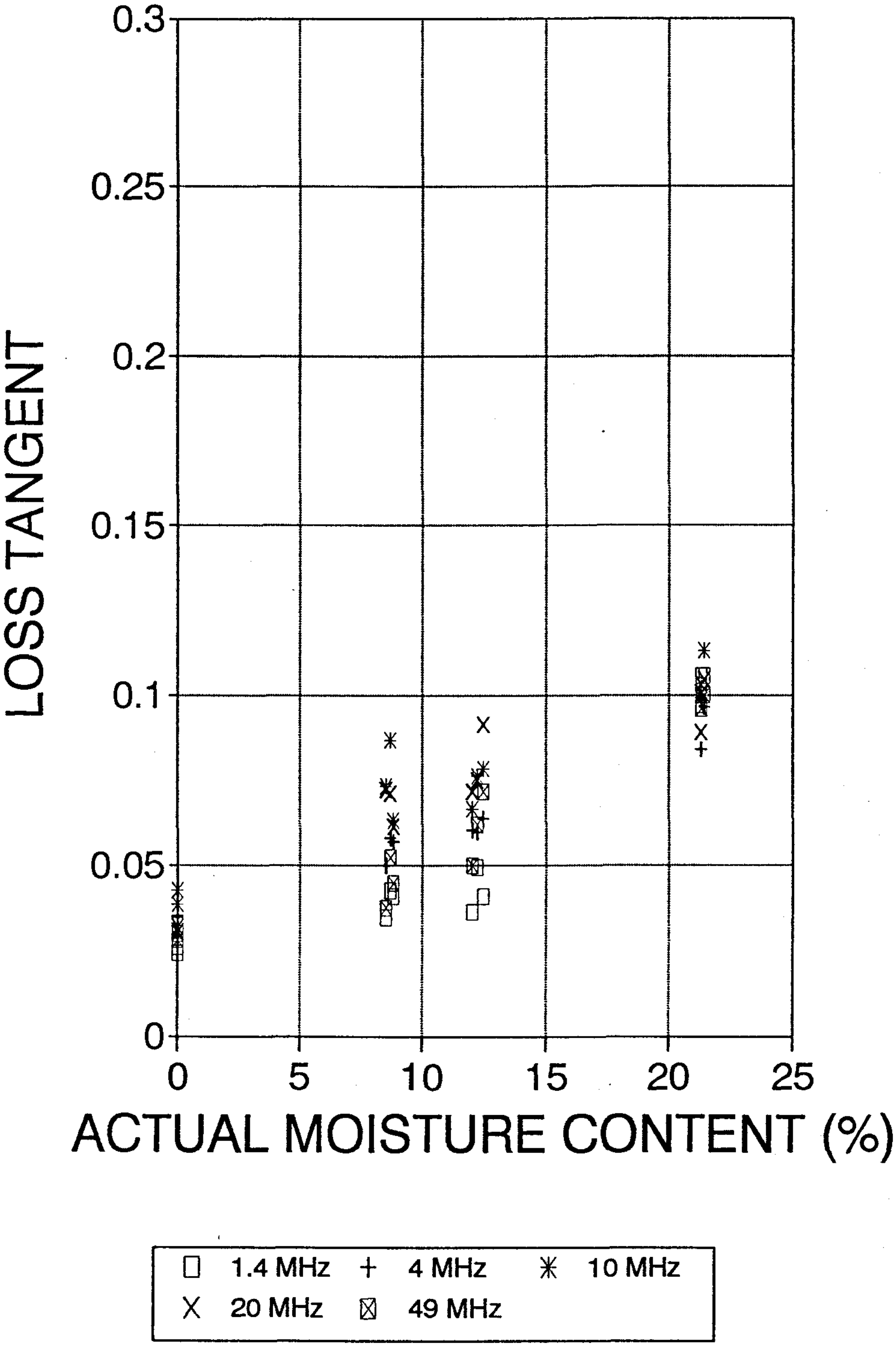

Figure A.3.6. Effect of moisture content on loss tangent for clear heartwood.

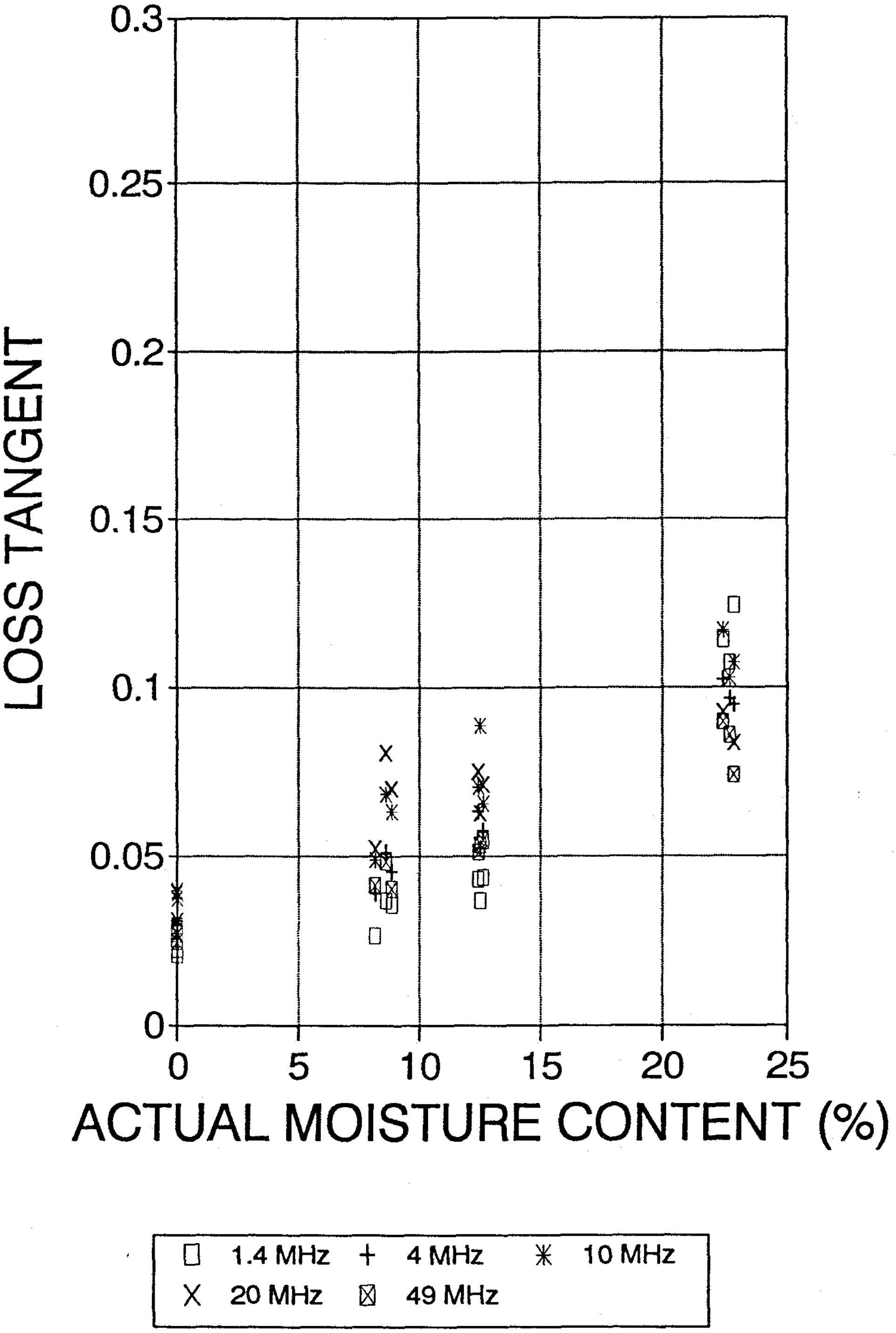

Figure A.3.7. Effect of moisture content on loss tangent for clear sapwood.

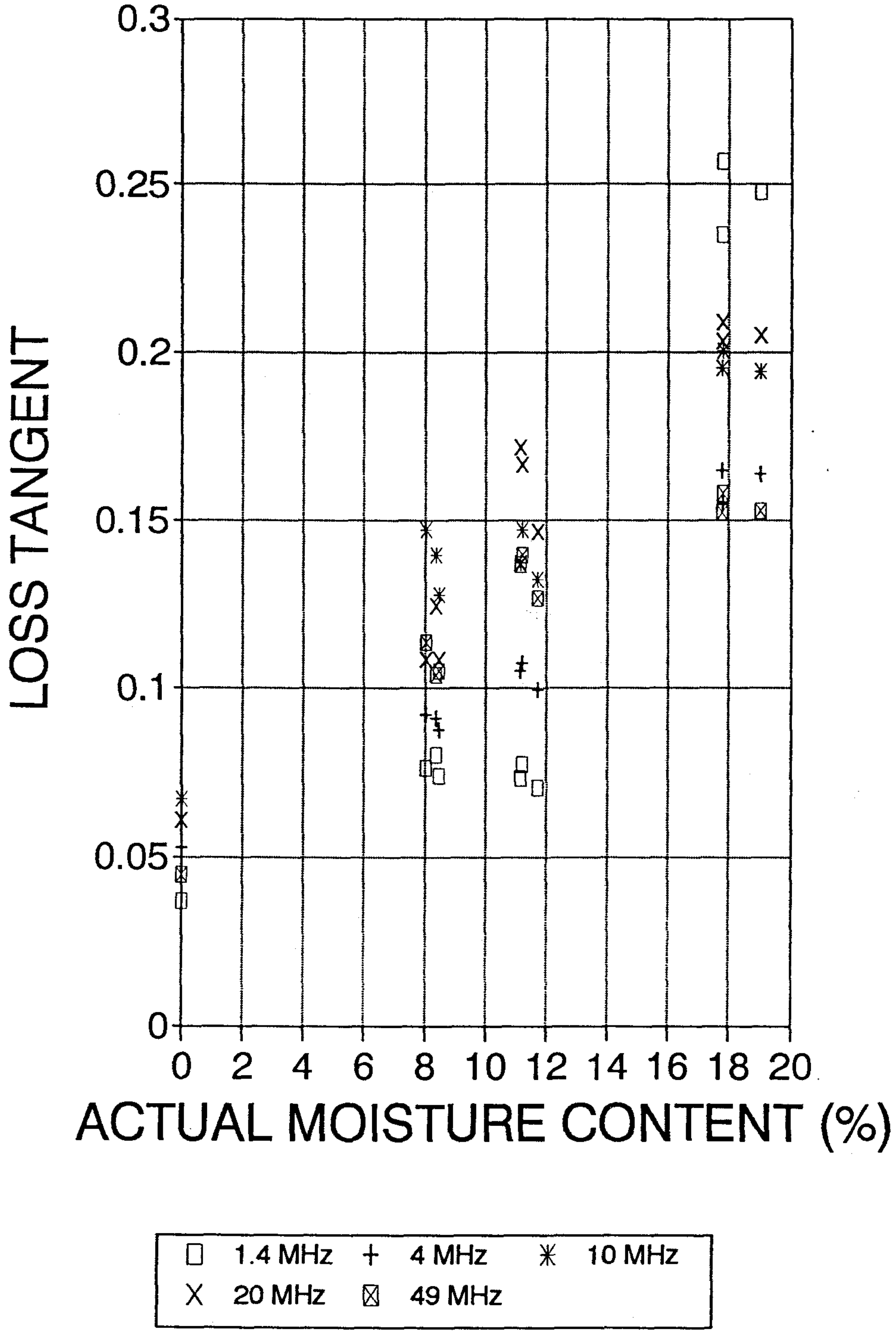

Figure A.3.8. Effect of moisture content on loss tangent for large tight knots.

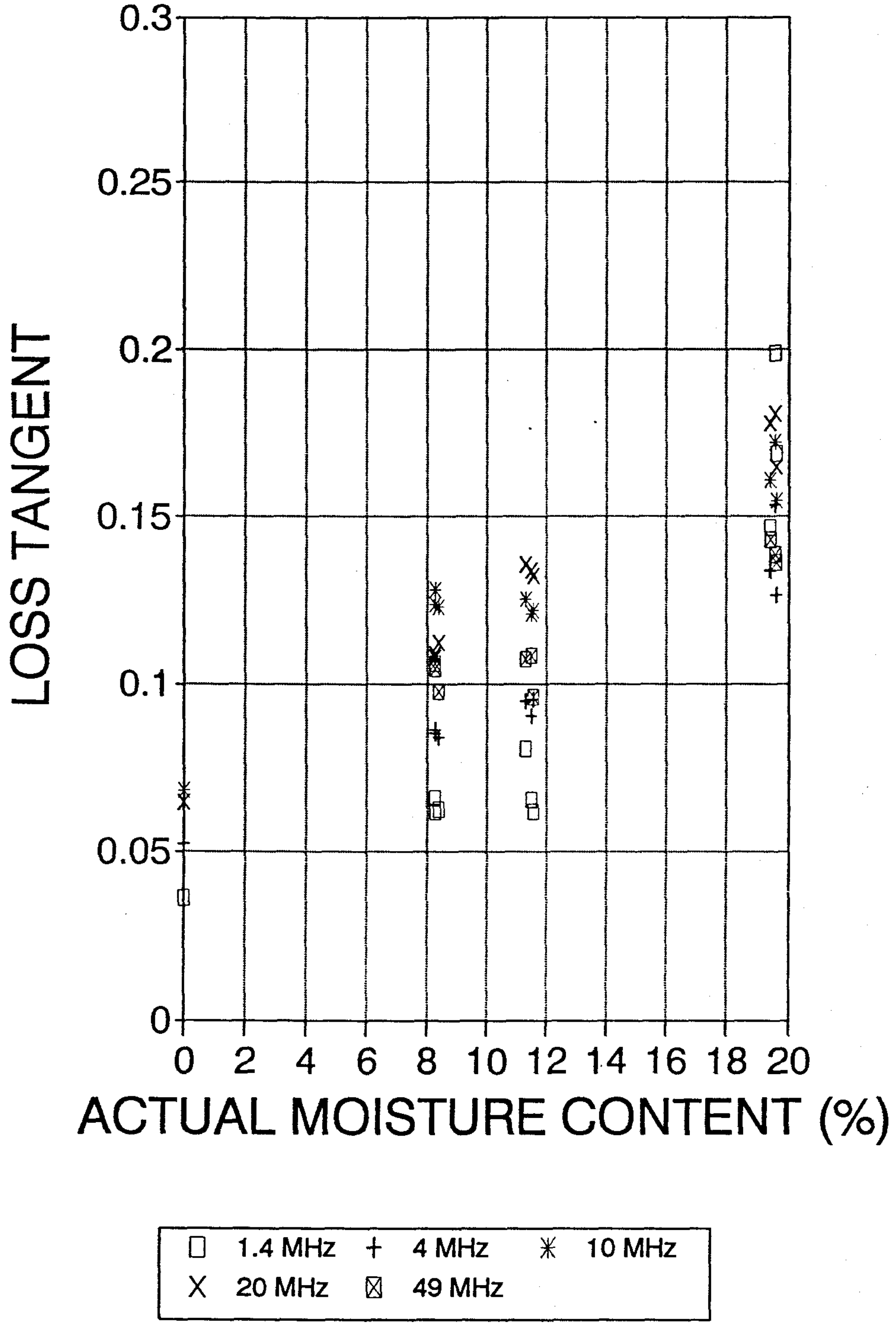

Figure A.3.9. Effect of moisture content on loss tangent for medium tight knots.

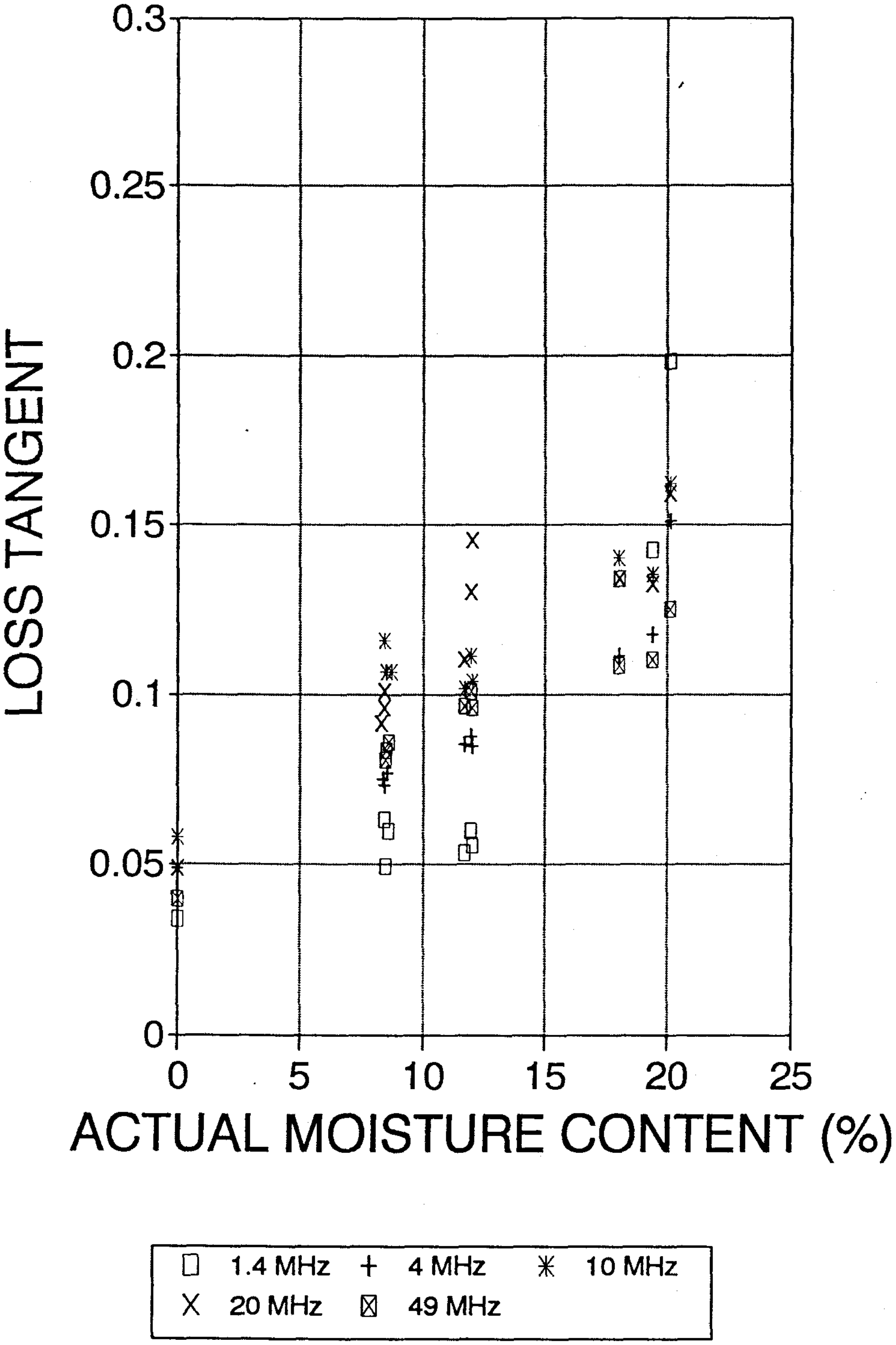

Figure A.3.10. Effect of moisture content on loss tangent for small tight knots.

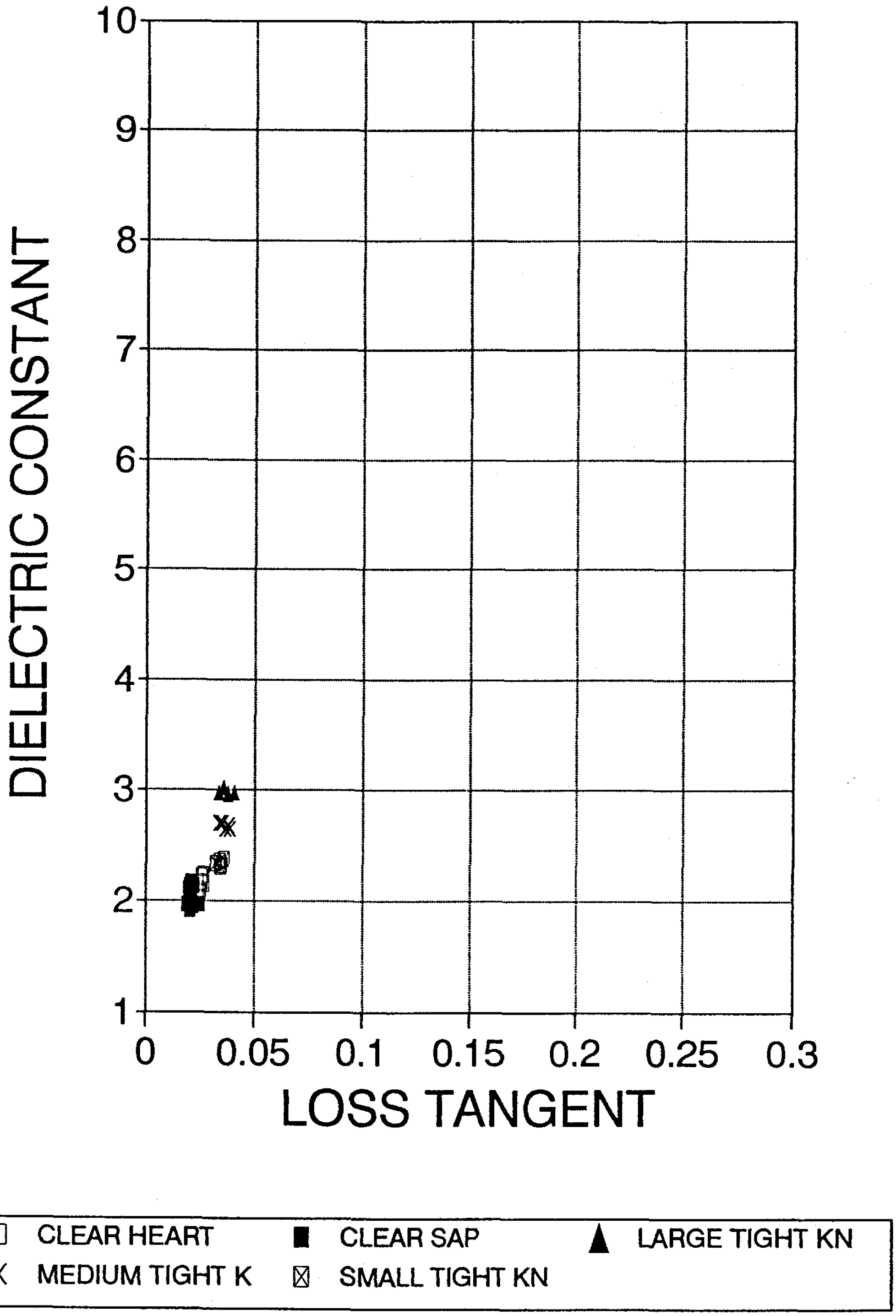

Figure A.3.11. Dielectric constant versus loss tangent at 0% MC and 1.4 MHz.

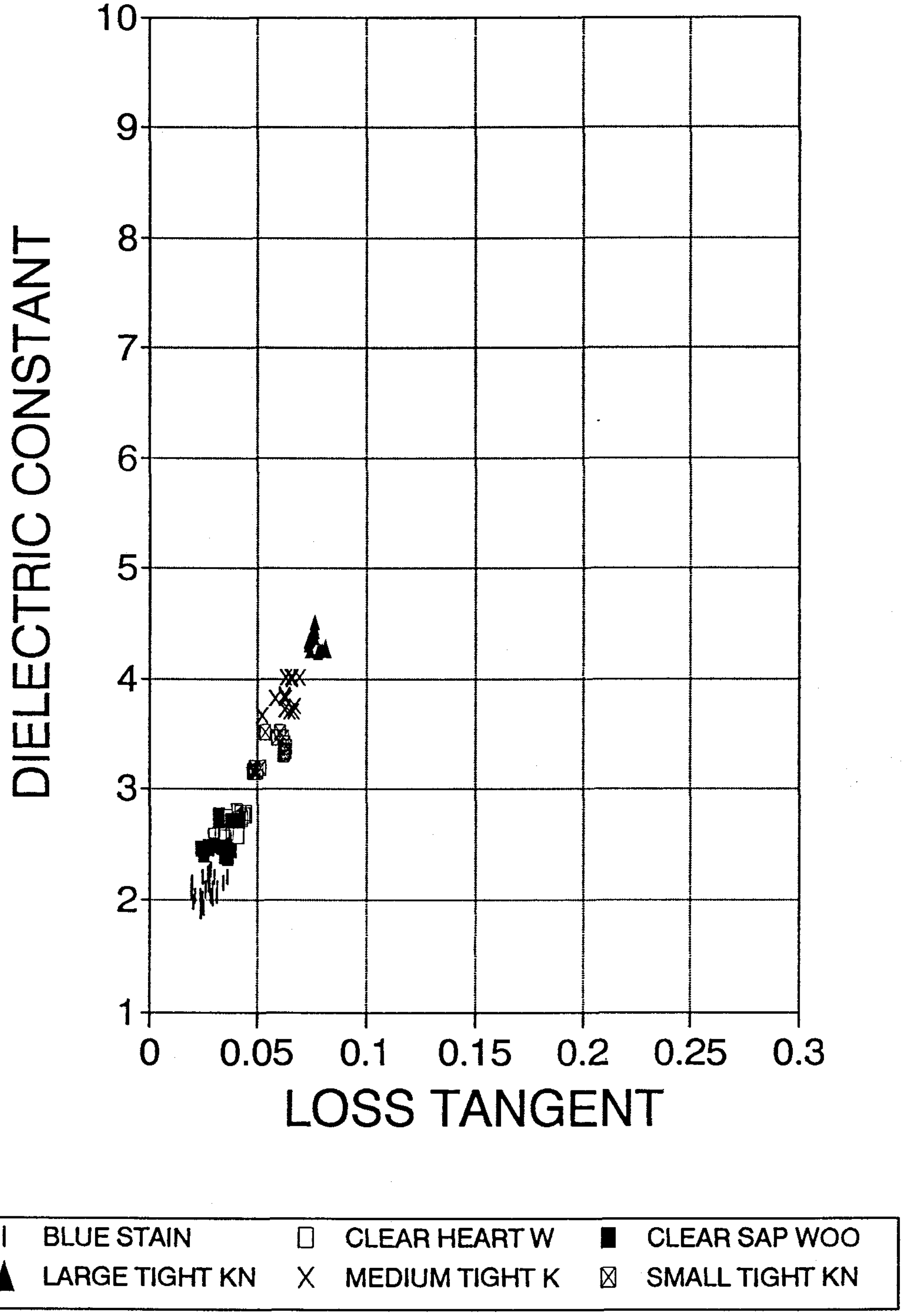

Figure A.3.12. Dielectric constant versus loss tangent at 6.6% MC (nominal) and 1.4 MHz.

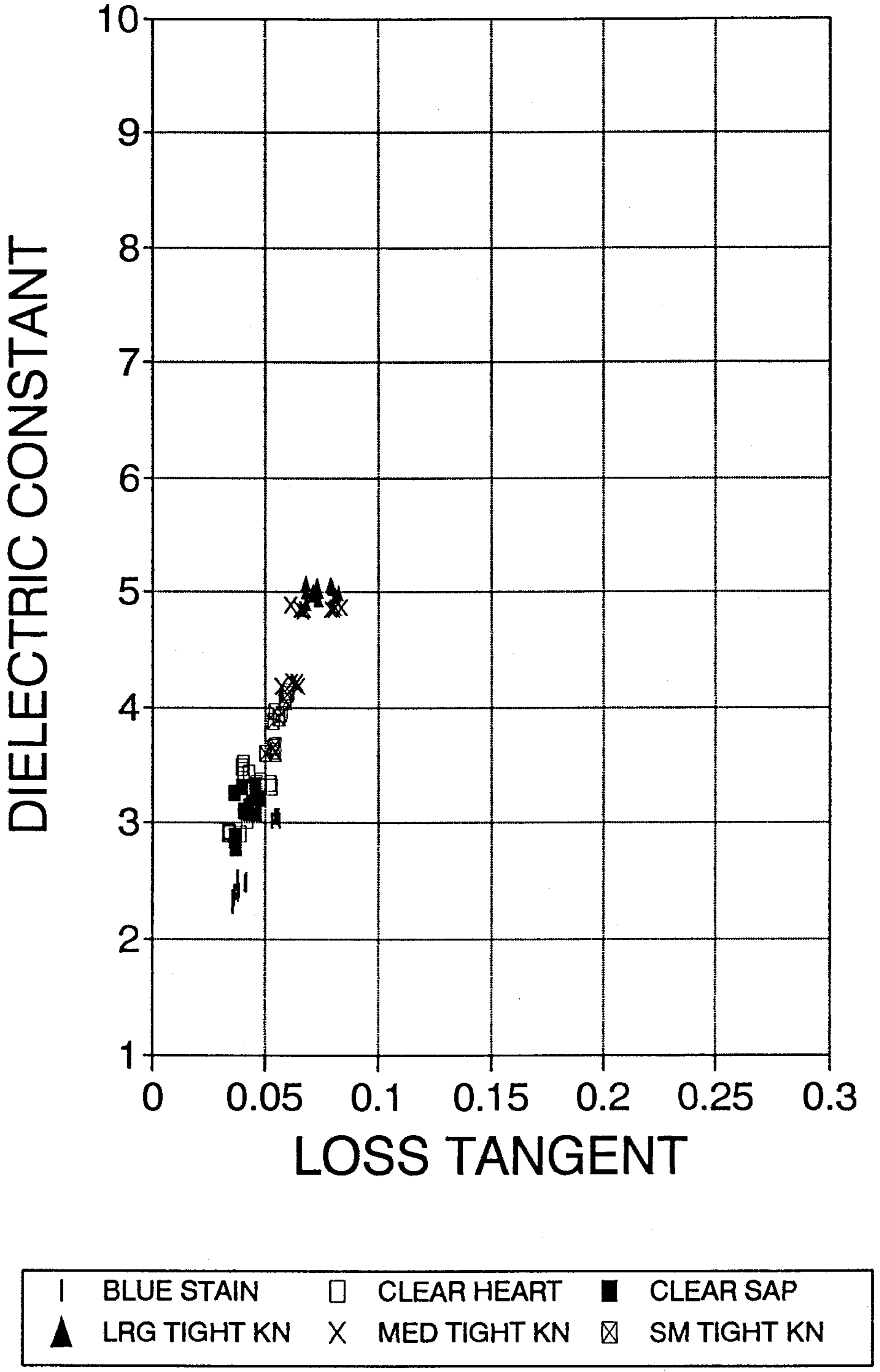

Figure A.3.13. Dielectric constant versus loss tangent at 10% MC (nominal) and 1.4 MHz.

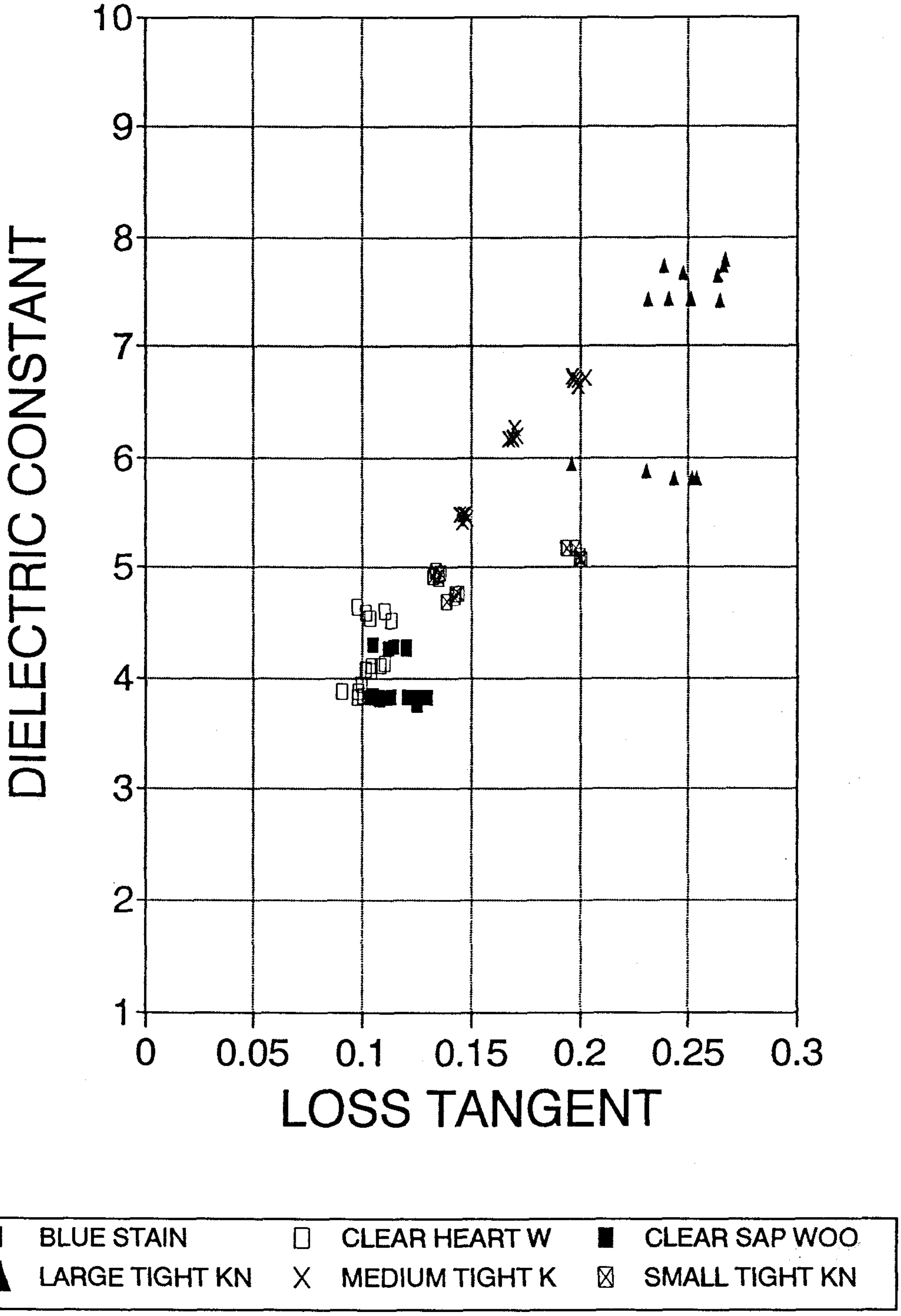

Figure A.3.14. Dielectric constant versus loss tangent at 25% MC (nominal) and 1.4 MHz.

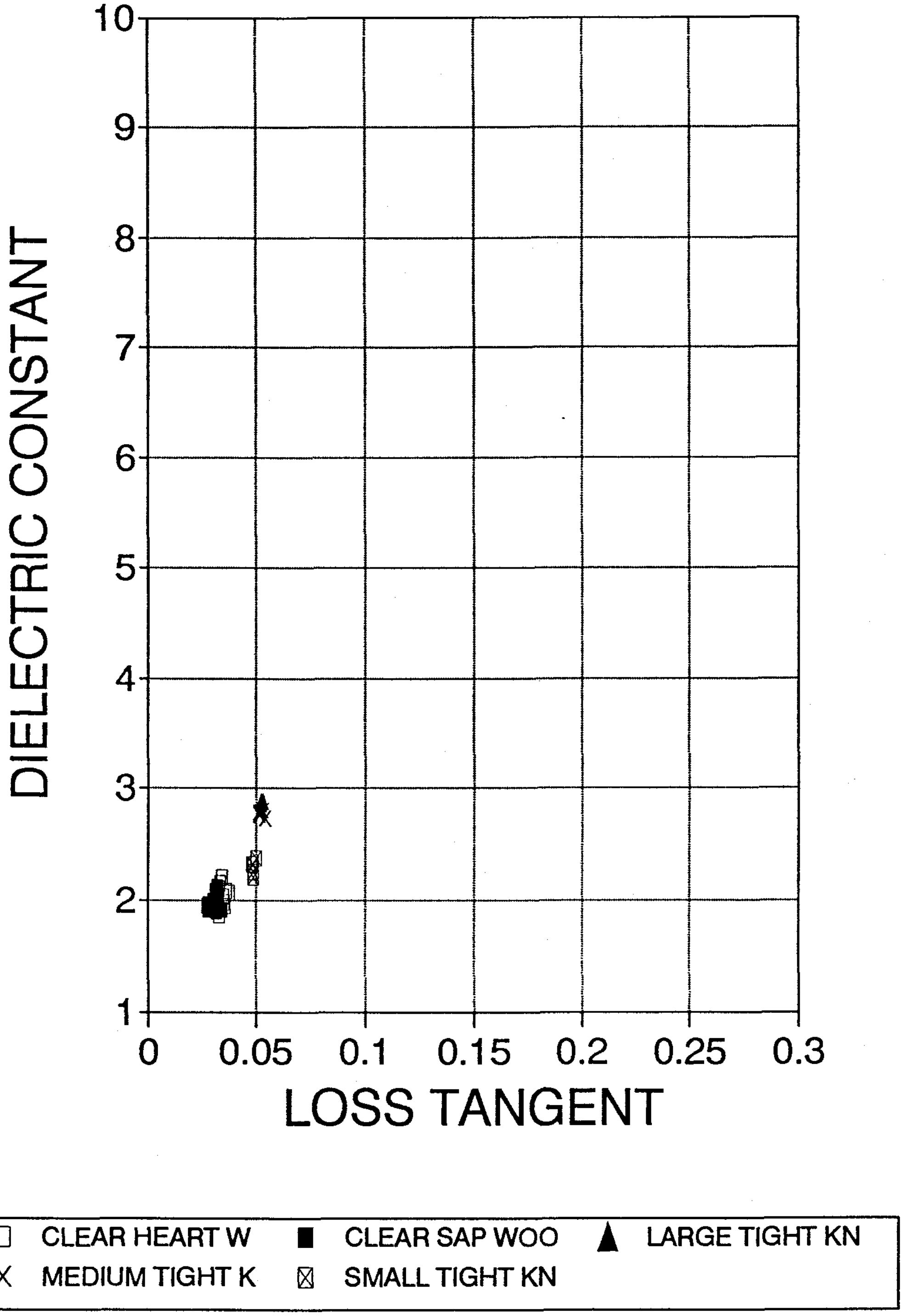

Figure A.3.15. Dielectric constant versus loss tangent at 0% MC and 4 MHz.

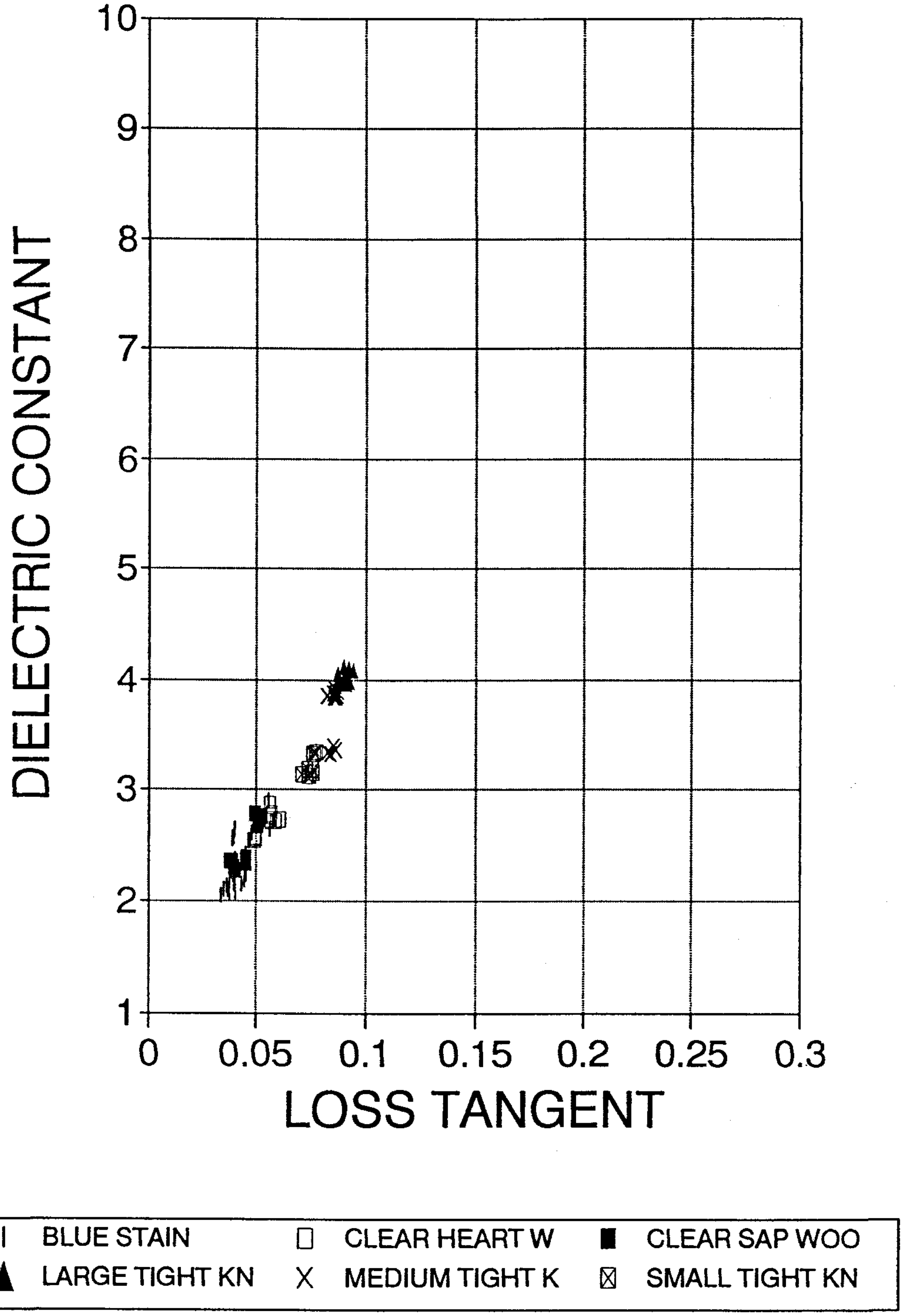

Figure A.3.16. Dielectric constant versus loss tangent at 6.6% MC (nominal) and 4 MHz.

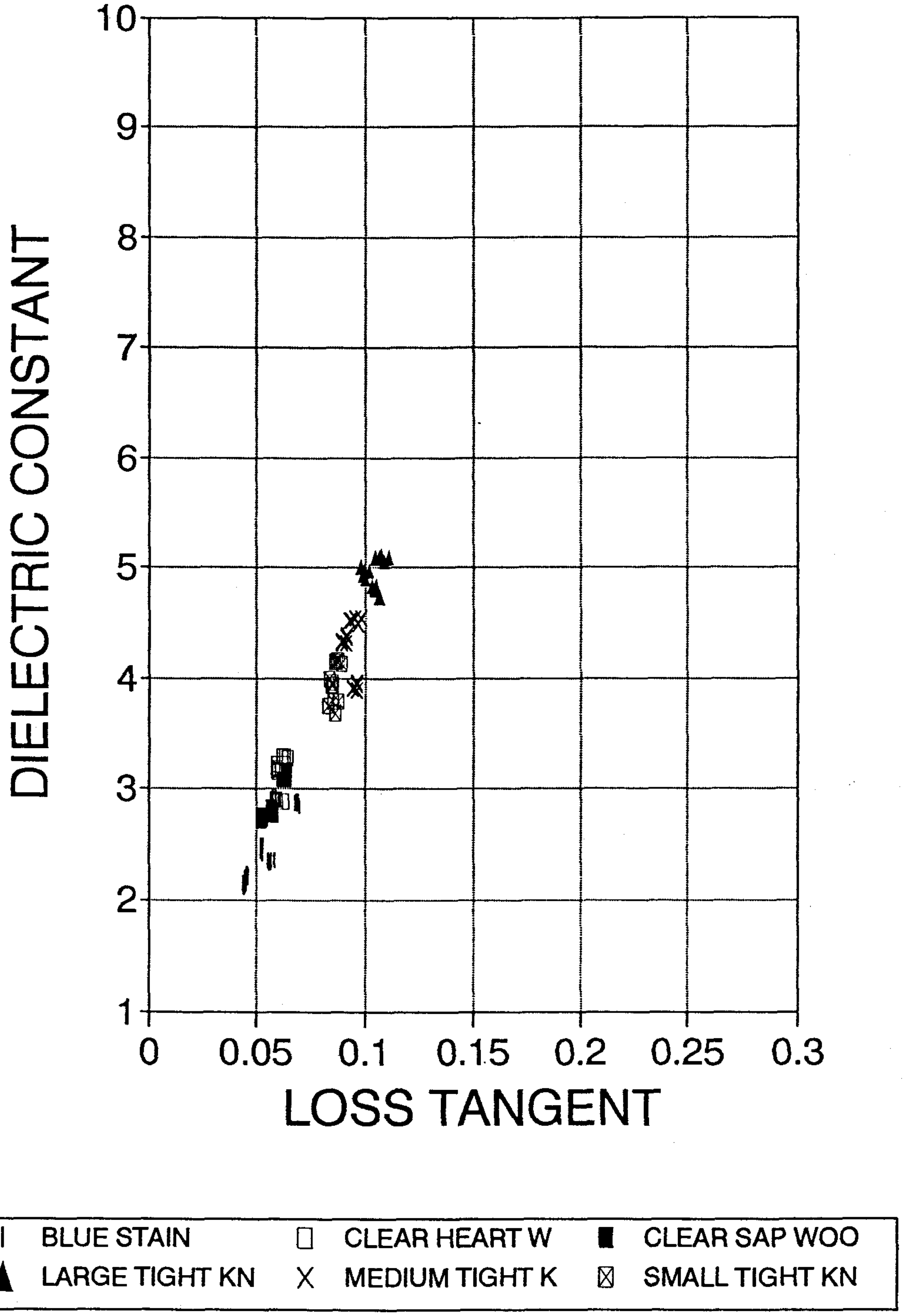

Figure A.3.17. Dielectric constant versus loss tangent at 10% MC (nominal) and 4 MHz.

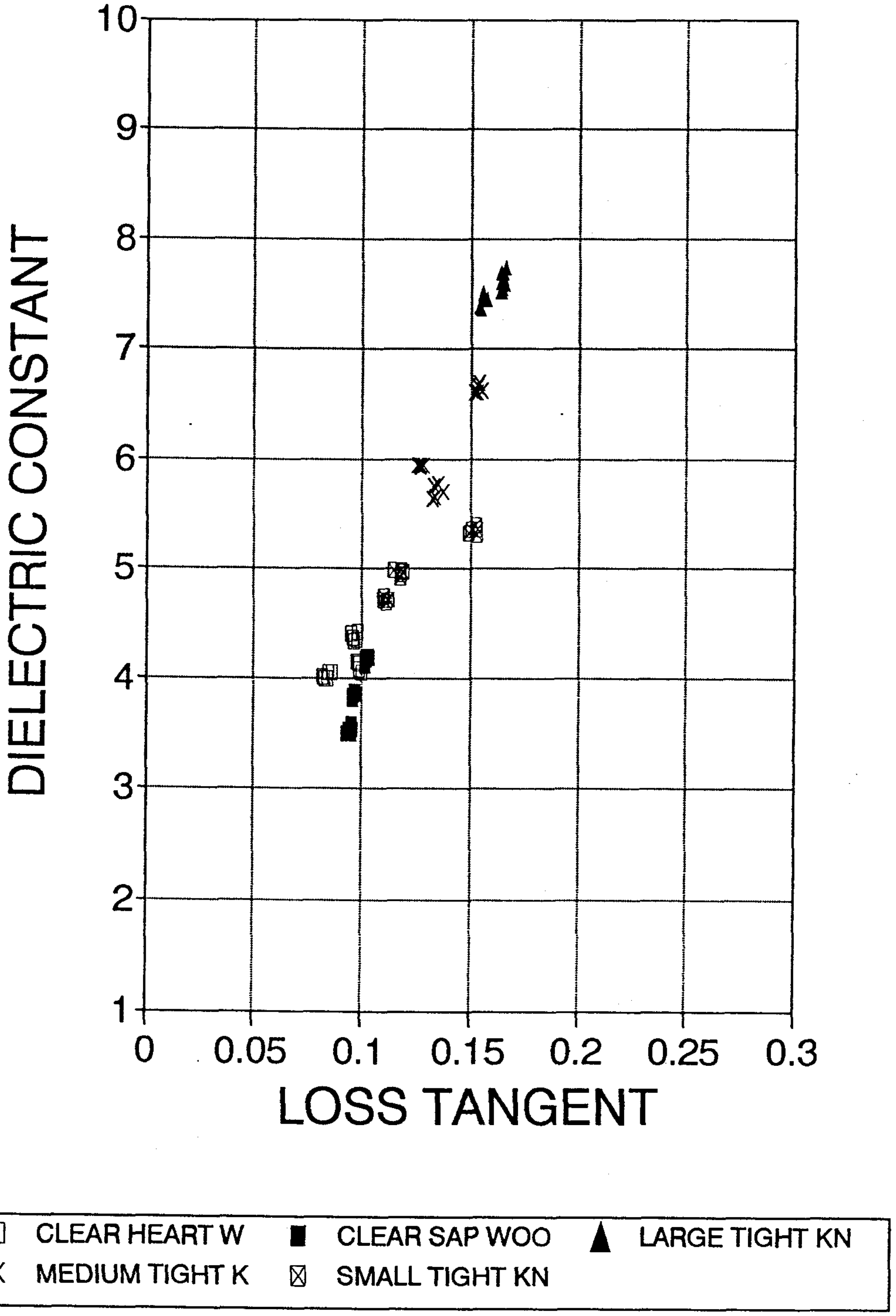

Figure A.3.18. Dielectric constant versus loss tangent at 25% MC (nominal) and 4 MHz.

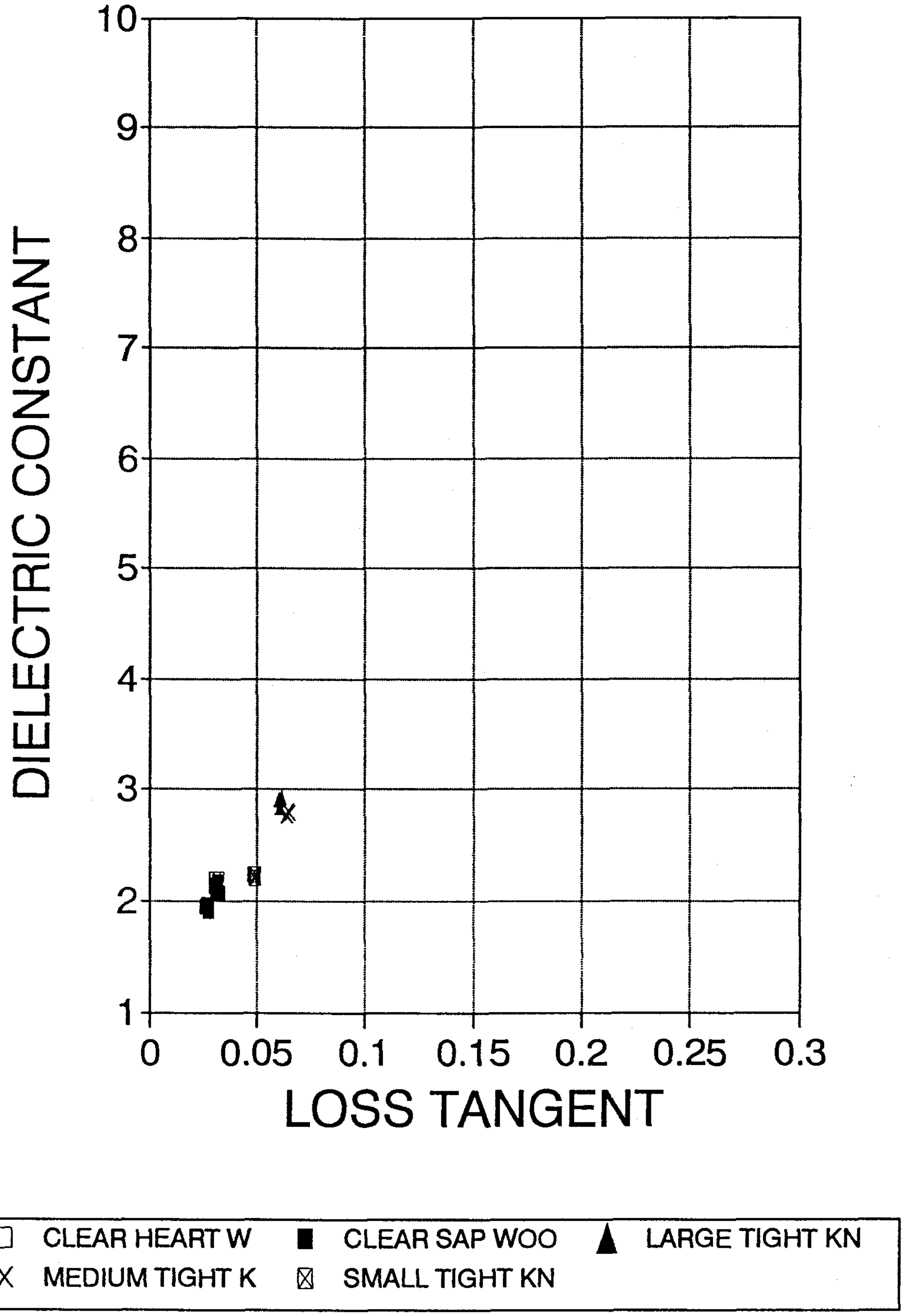

Figure A.3.19. Dielectric constant versus loss tangent at 0% MC and 10 MHz.

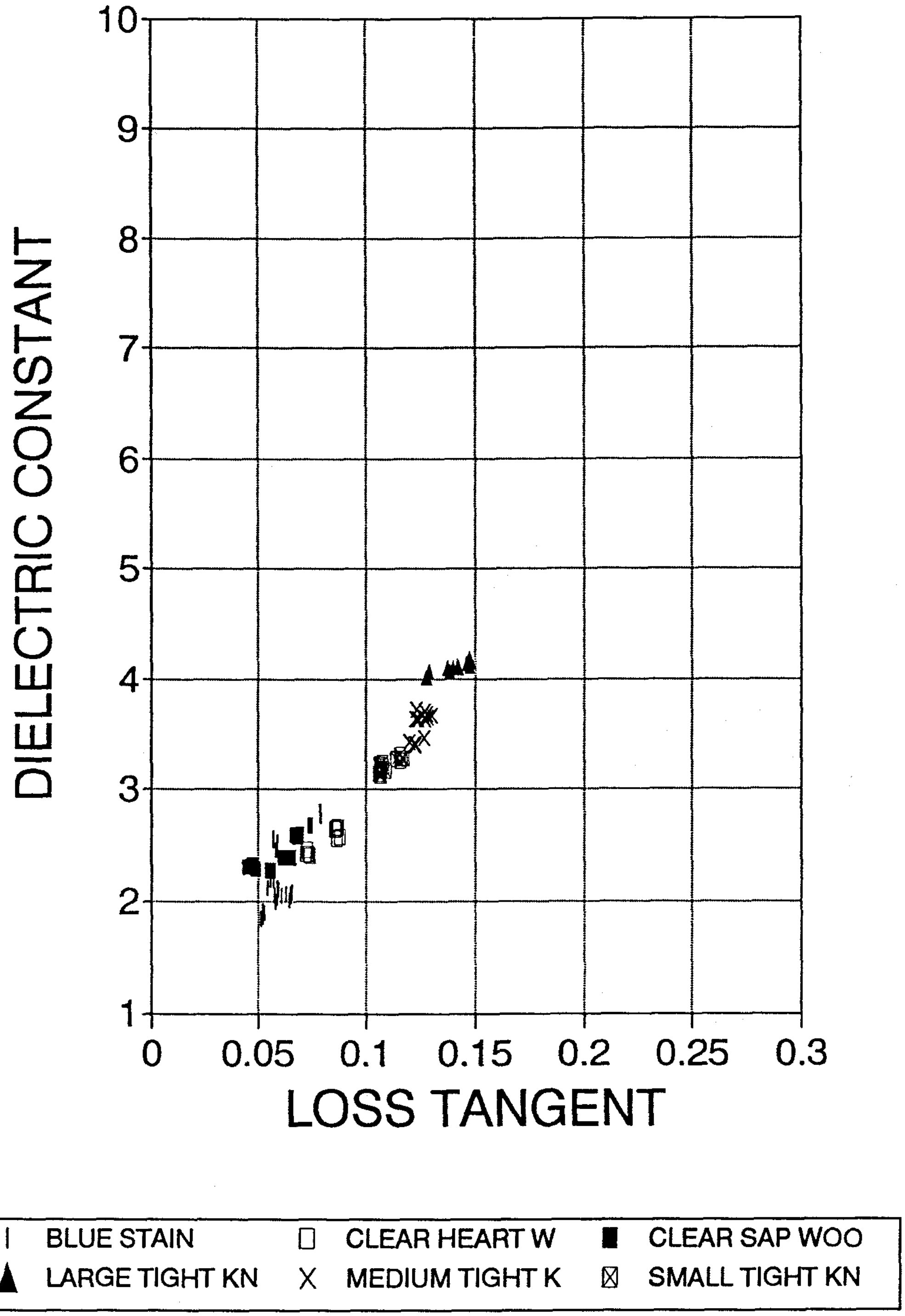

Figure A.3.20. Dielectric constant versus loss tangent at 6.6% MC (nominal) and 10 MHz.

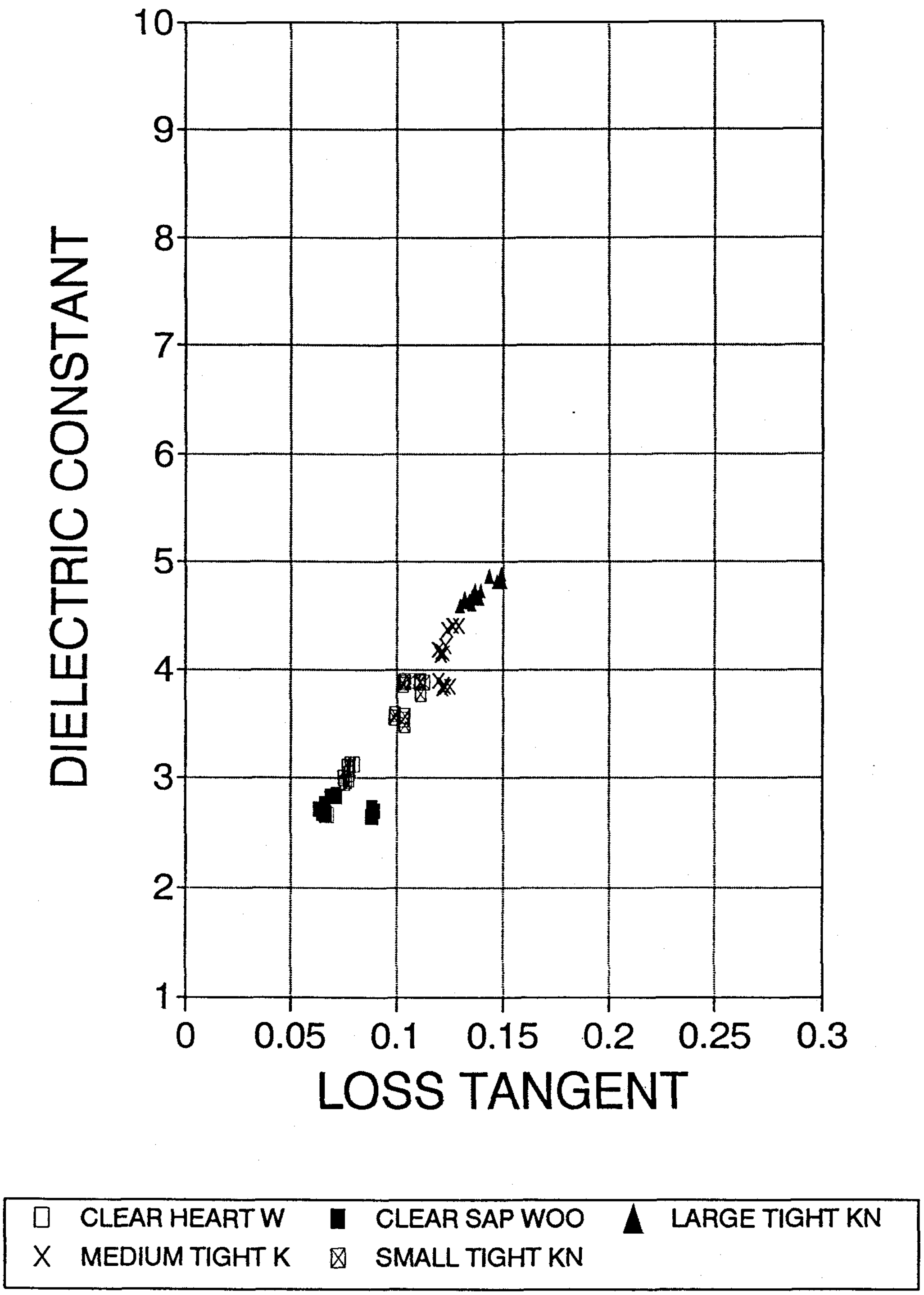

Figure A.3.21. Dielectric constant versus loss tangent at 10% MC (nominal) and 10 MHz.

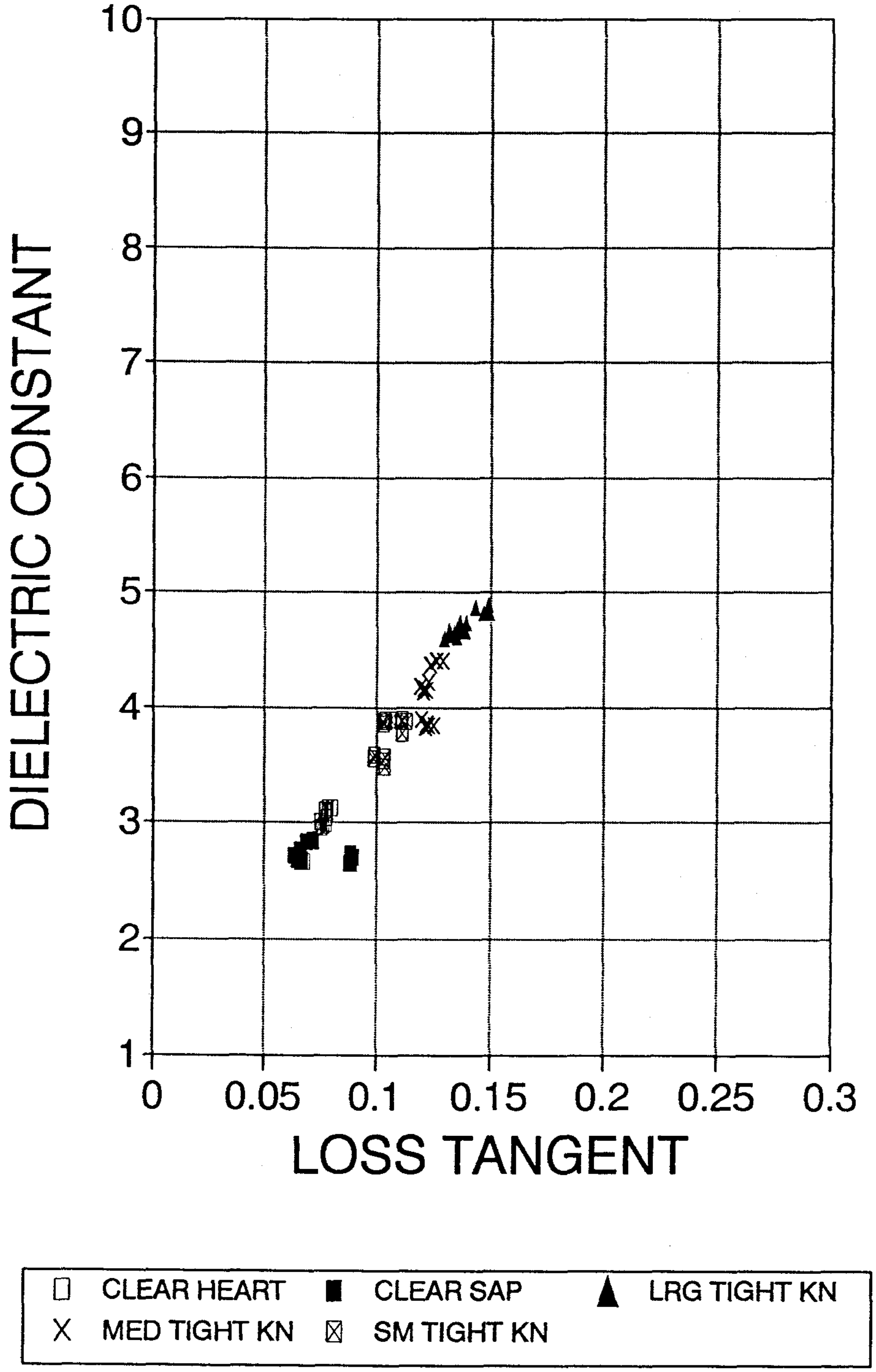

Figure A.3.22. Dielectric constant versus loss tangent at 25% MC (nominal) and 10 MHz.

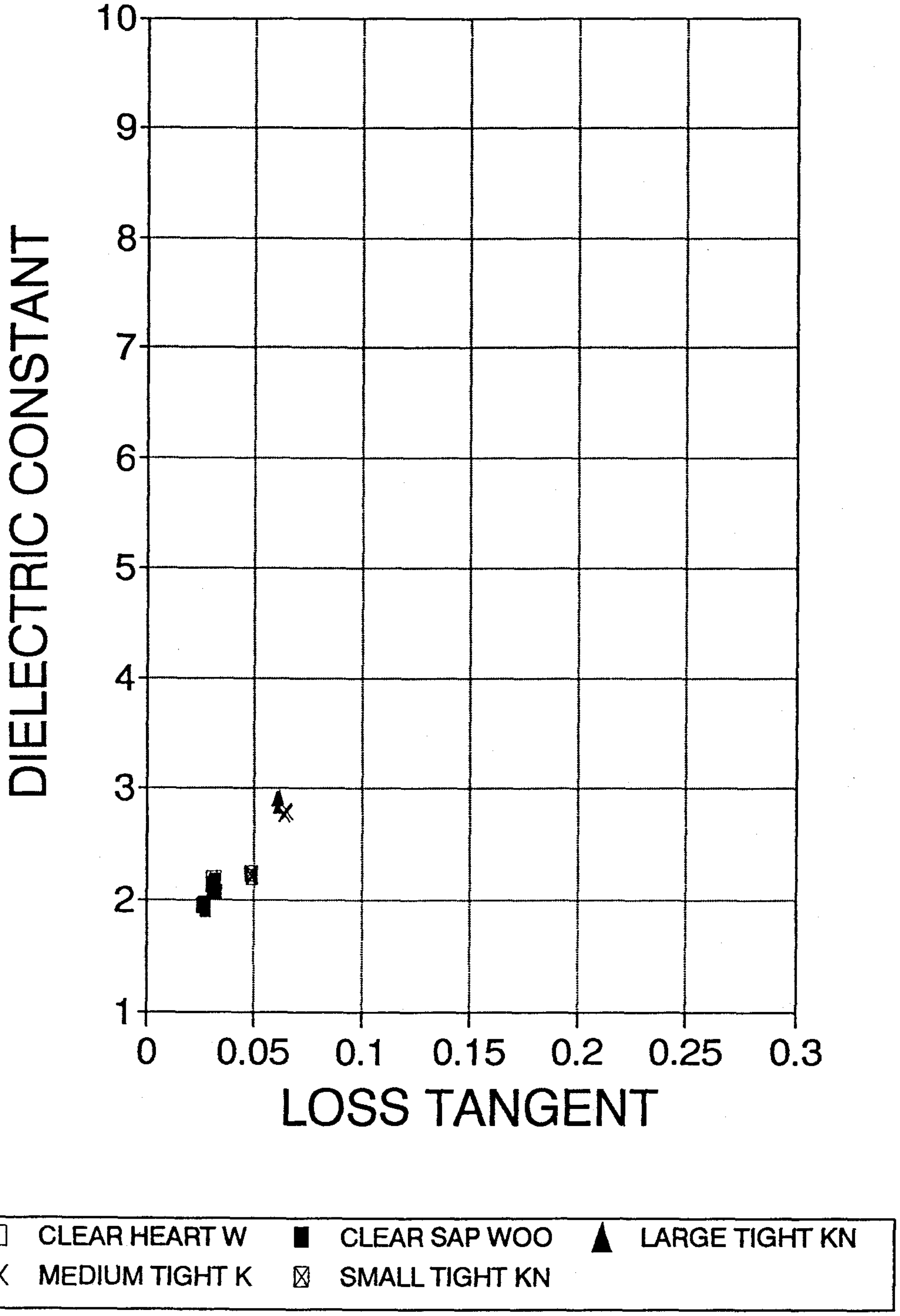

Figure A.3.23. Dielectric constant versus loss tangent at 0% MC and 20 MHz.

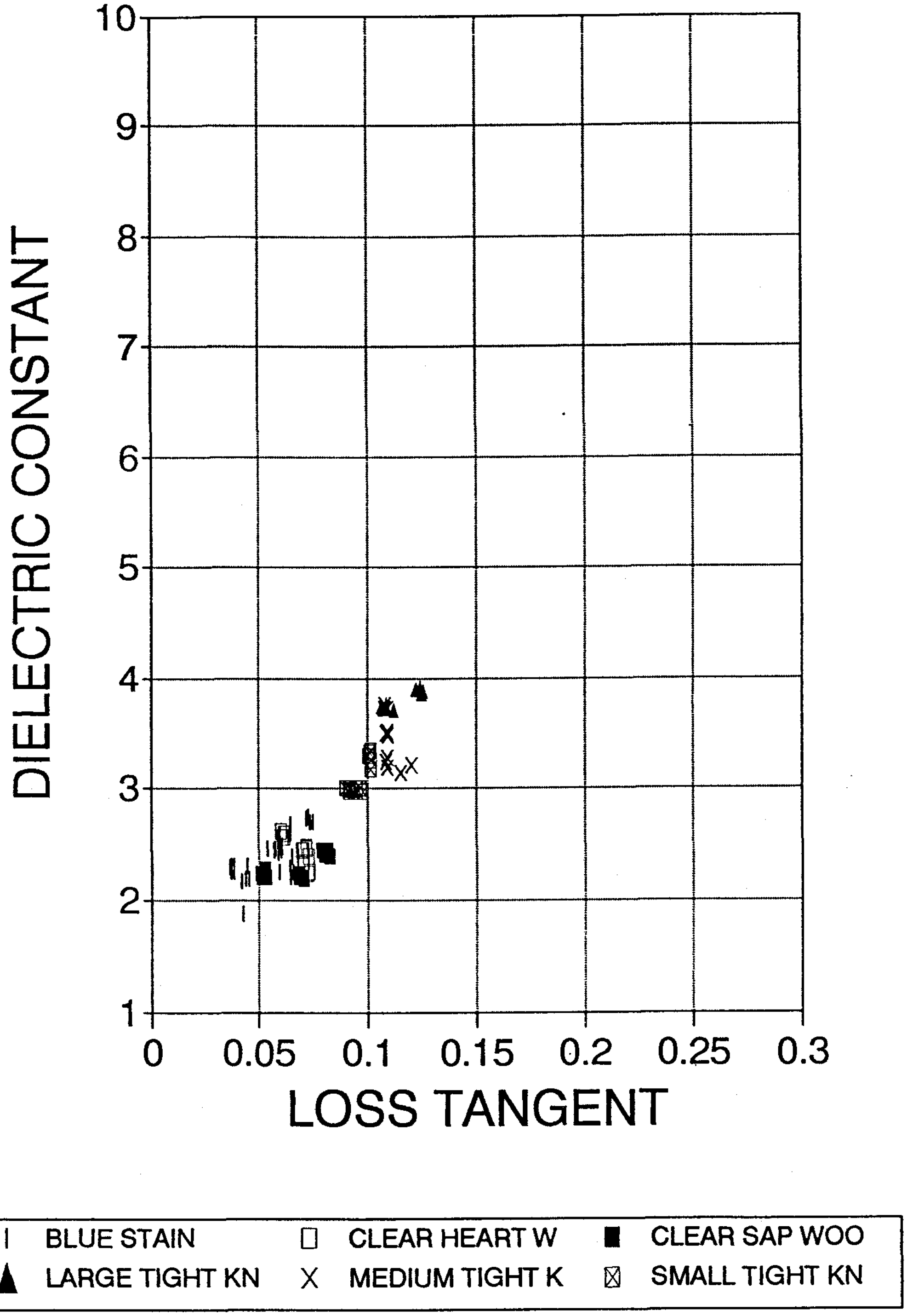

Figure A.3.24. Dielectric constant versus loss tangent at 6.6% MC (nominal) and 20 MHz.

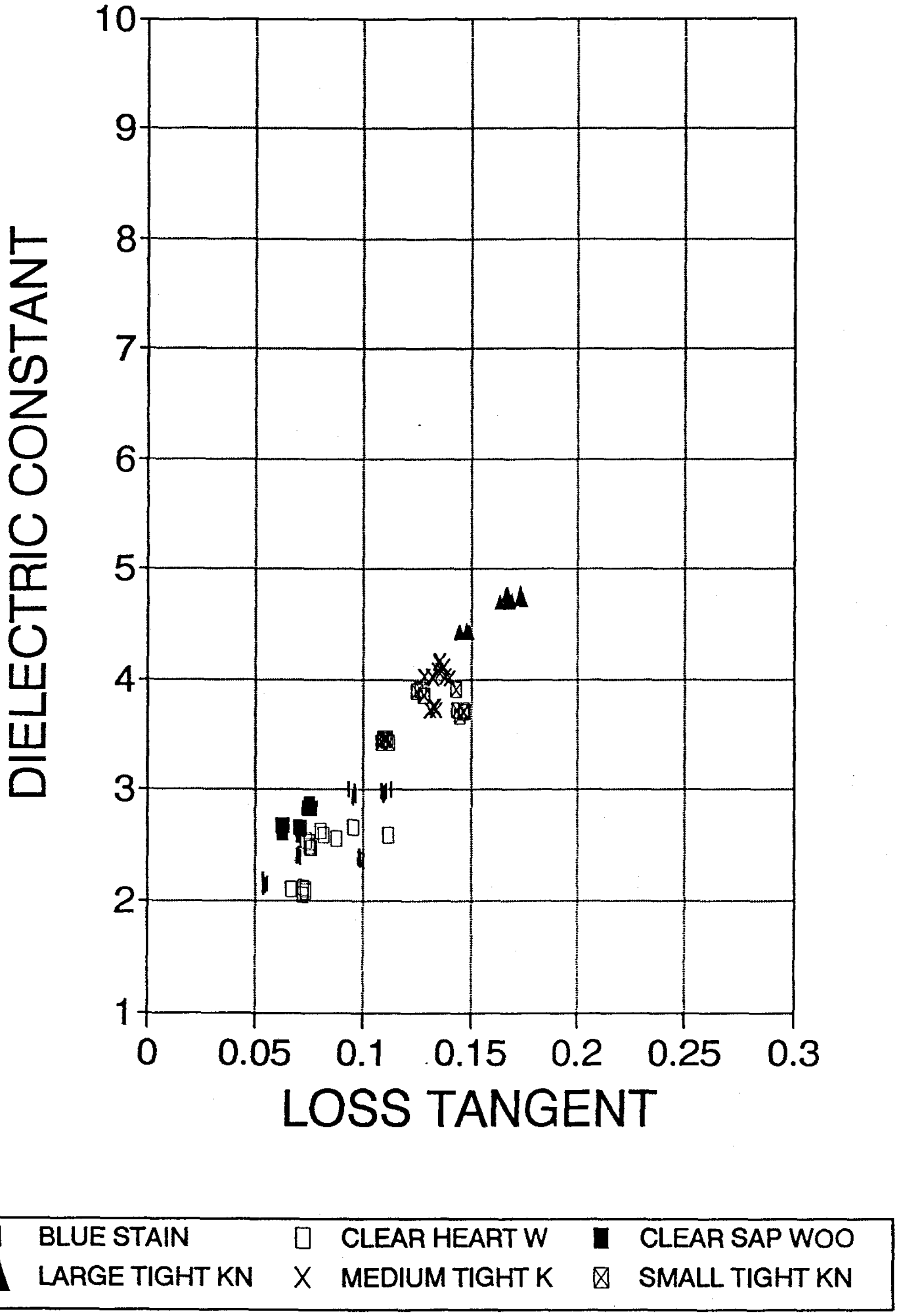

Figure A.3.25. Dielectric constant versus loss tangent at 10% MC (nominal) and 20 MHz.

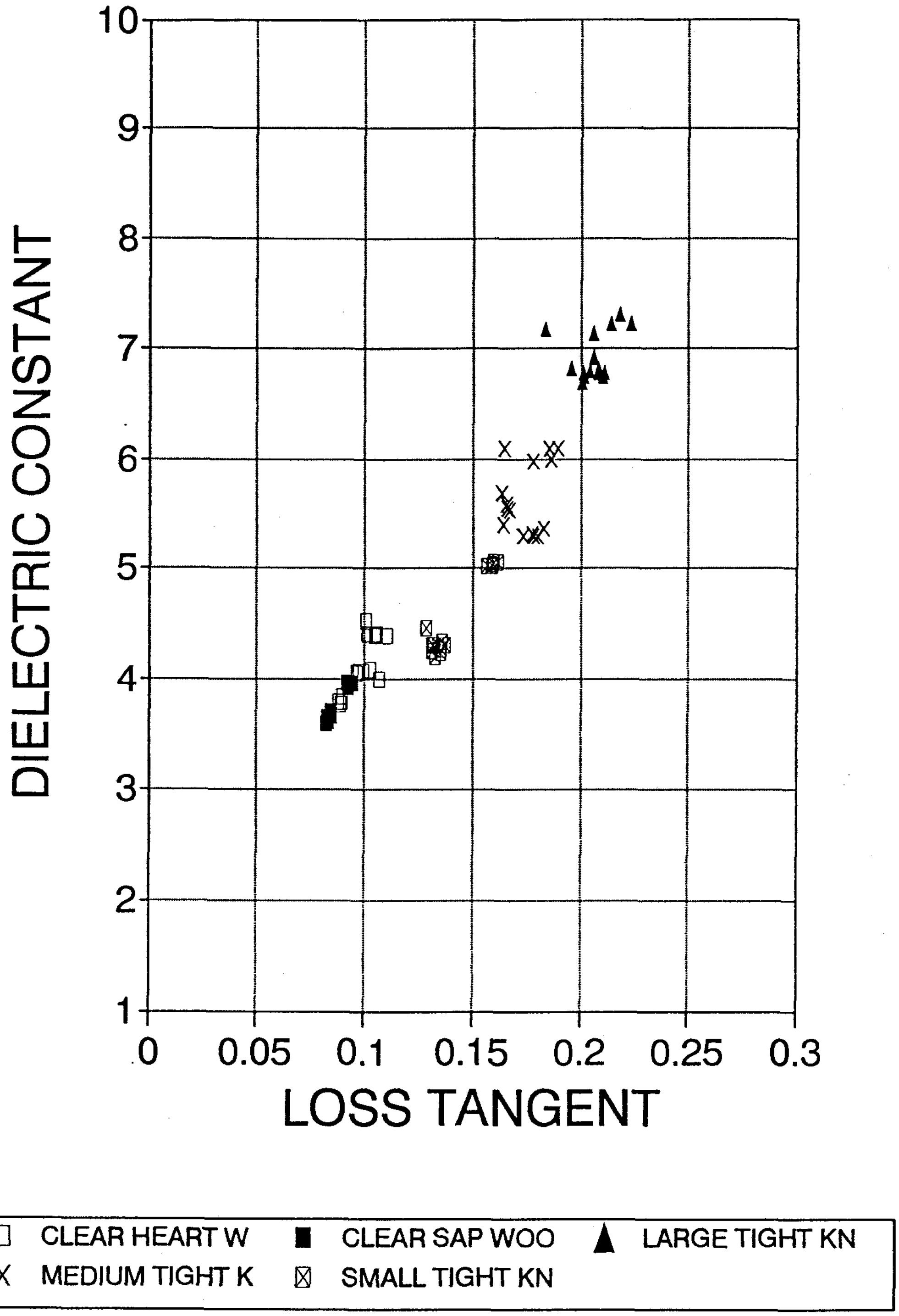

Figure A.3.26. Dielectric constant versus loss tangent at 25% MC (nominal) and 20 MHz.

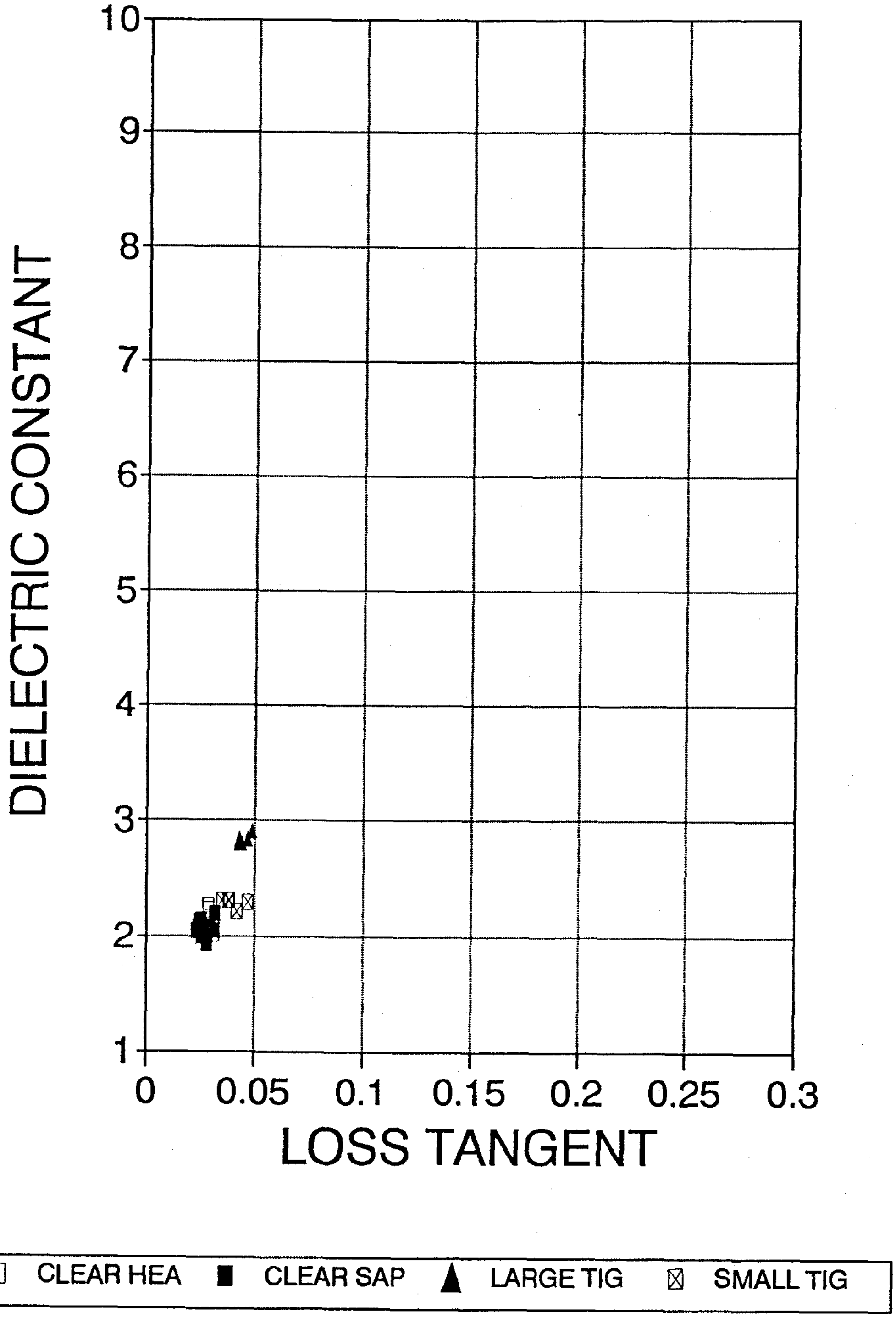

Figure A.3.27. Dielectric constant versus loss tangent at 0% MC and 49 MHz.

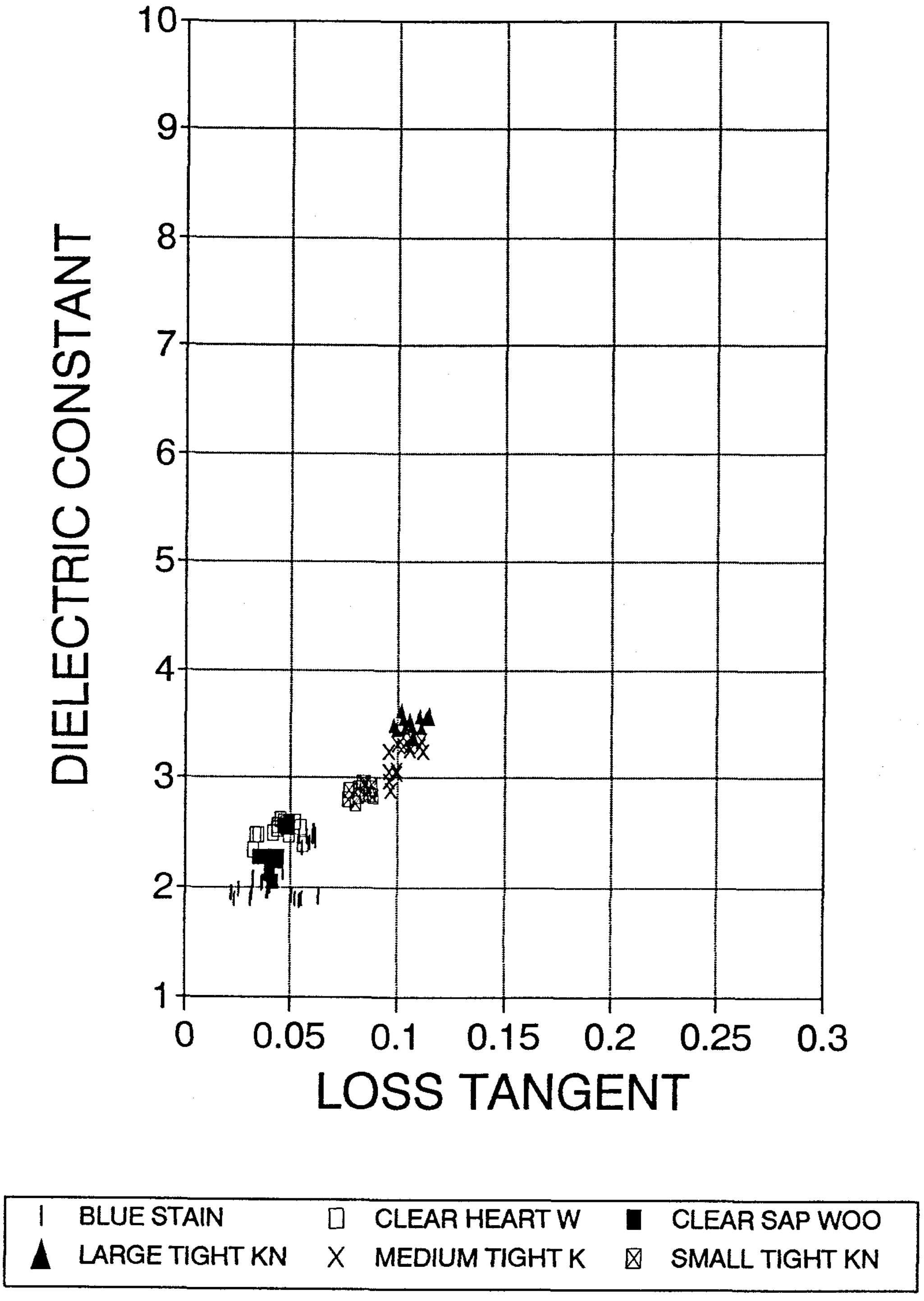

Figure A.3.28. Dielectric constant versus loss tangent at 6.6% MC (nominal) and 49 MHz.

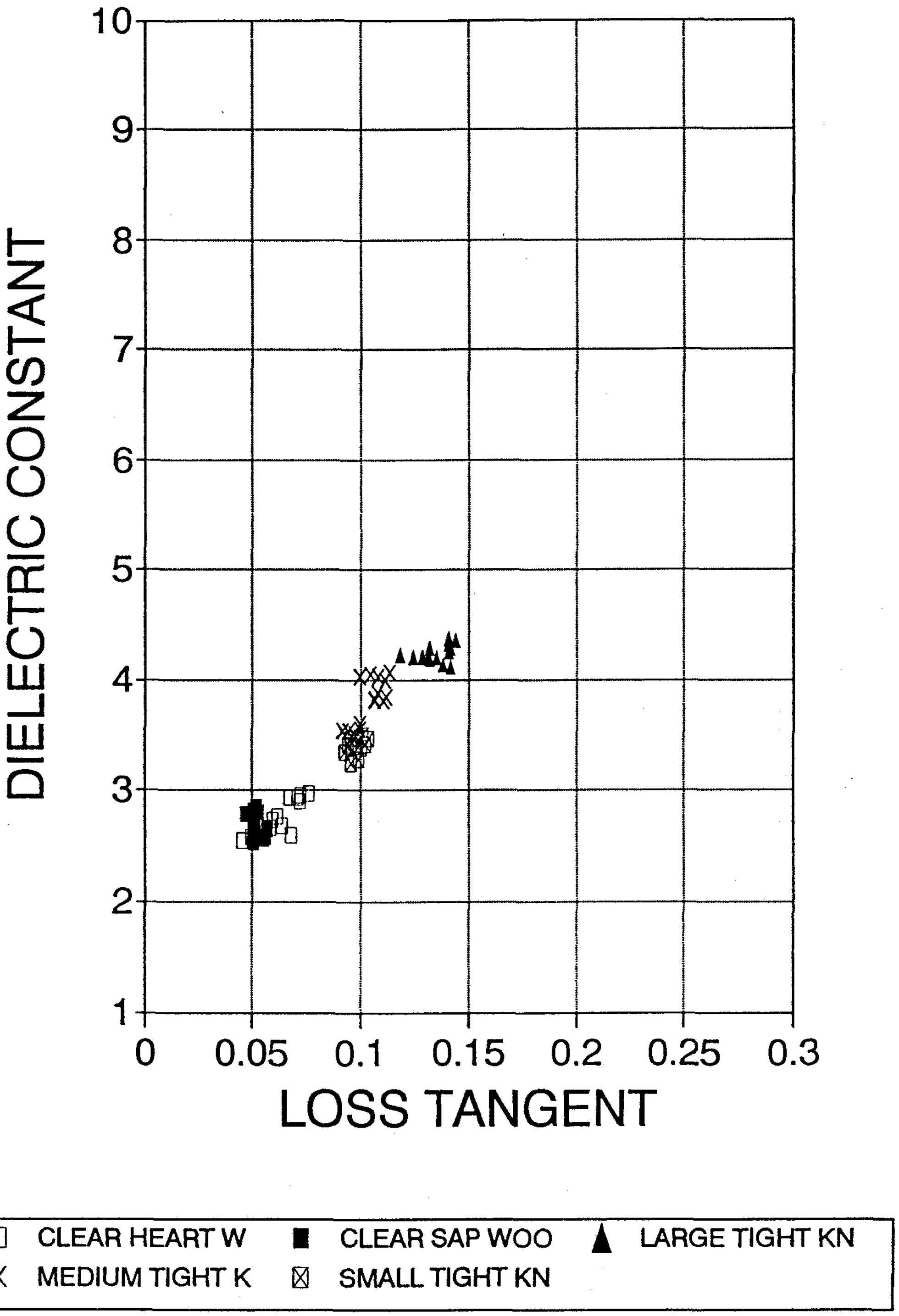

Figure A.3.29. Dielectric constant versus loss tangent at 10% MC (nominal) and 49 MHz.

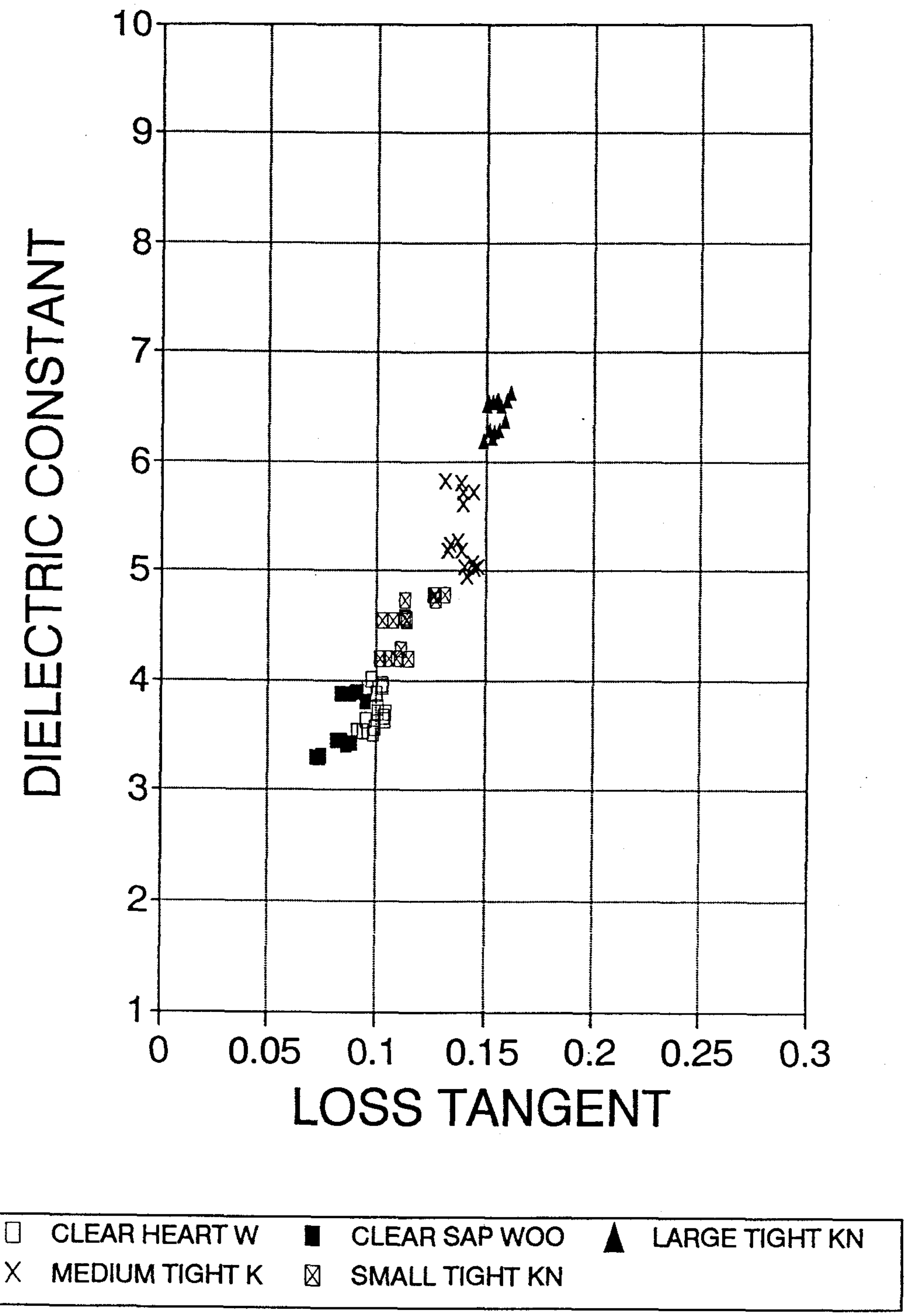

Figure A.3.30. Dielectric constant versus loss tangent at 25% MC (nominal) and 49 MHz.

APPENDIX 4: EXTENDED EXPERIMENT: RELATIONSHIP BETWEEN MOISTURE CONTENT AND FREQUENCY FOR WOOD FEATURES.

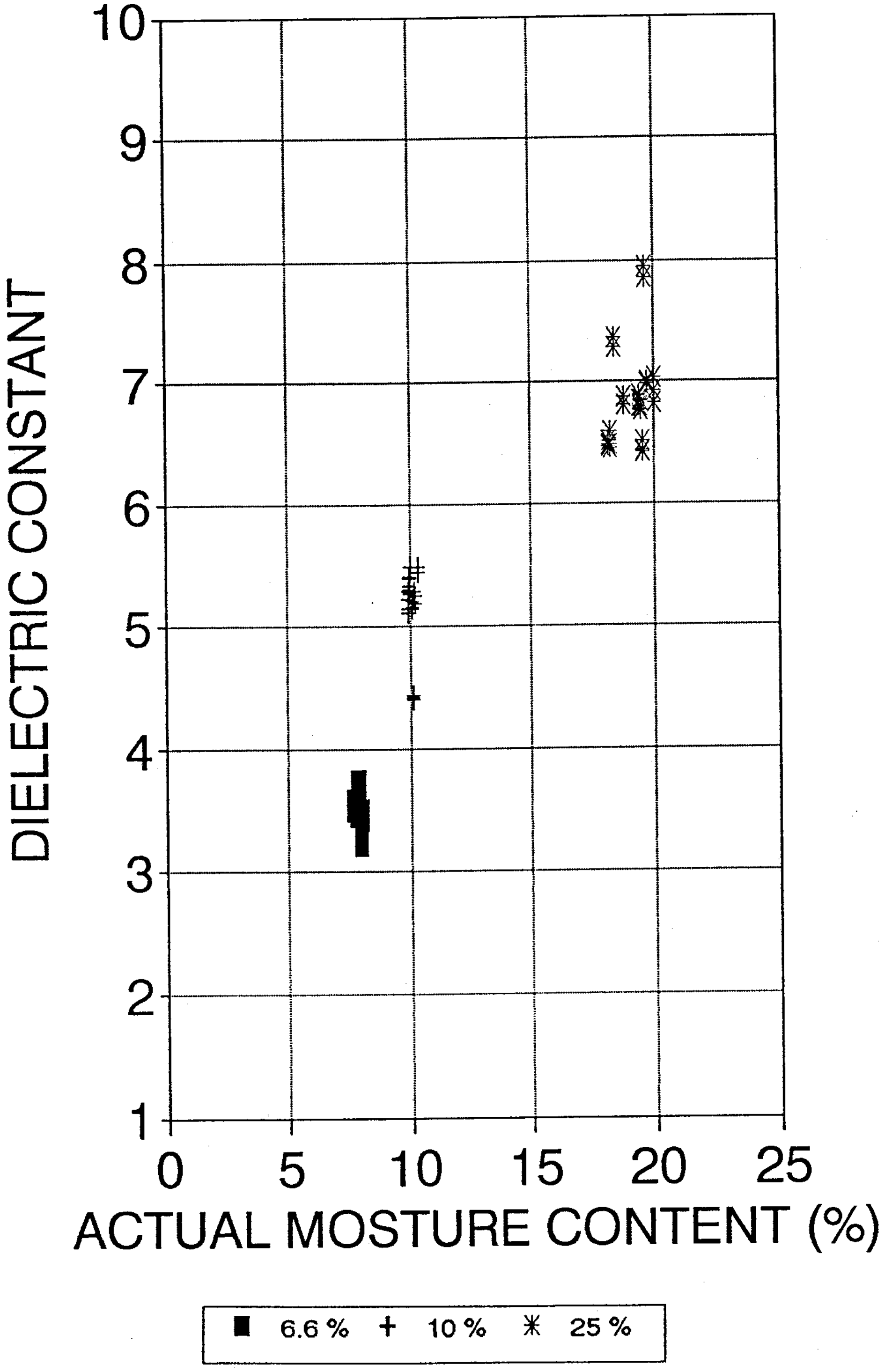

Figure A.4.1. The effect of moisture on the dielectric constant of large loose knots at 1.4 MHz.

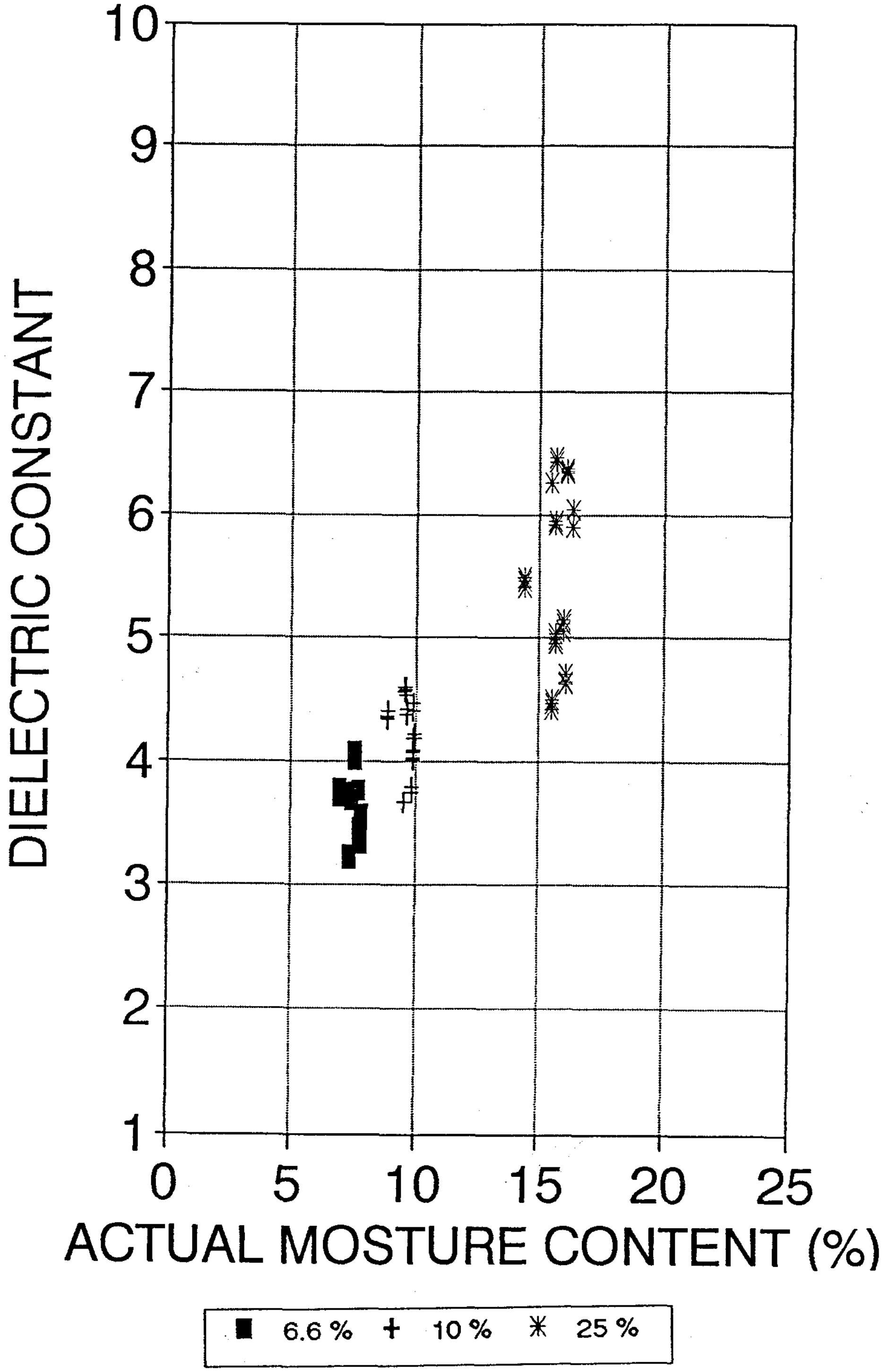

Figure A.4.2. The effect of moisture on the dielectric constant of medium loose knots at 1.4 MHz.

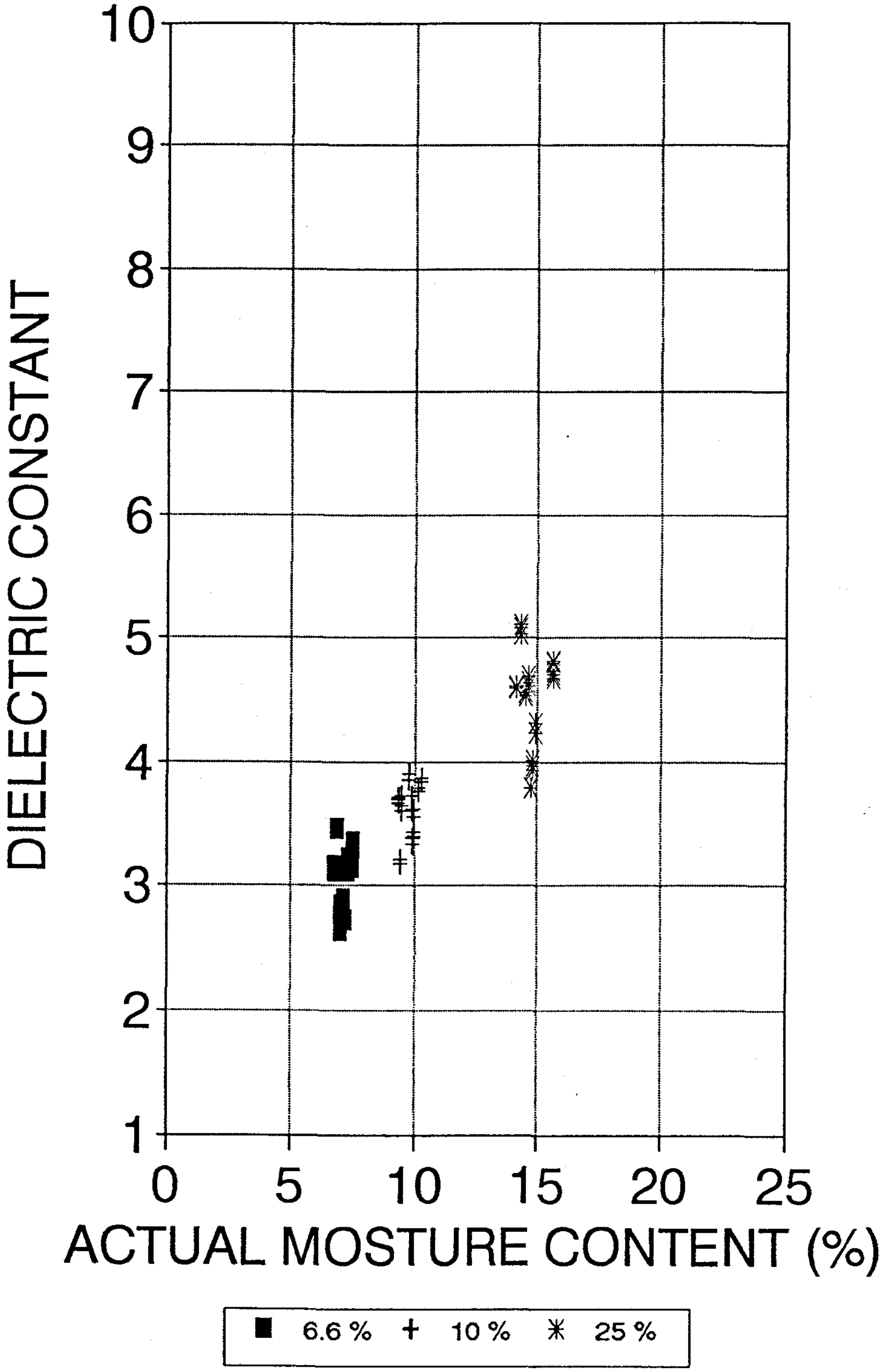

Figure A.4.3. The effect of moisture on the dielectric constant of small loose knots at 1.4 MHz.

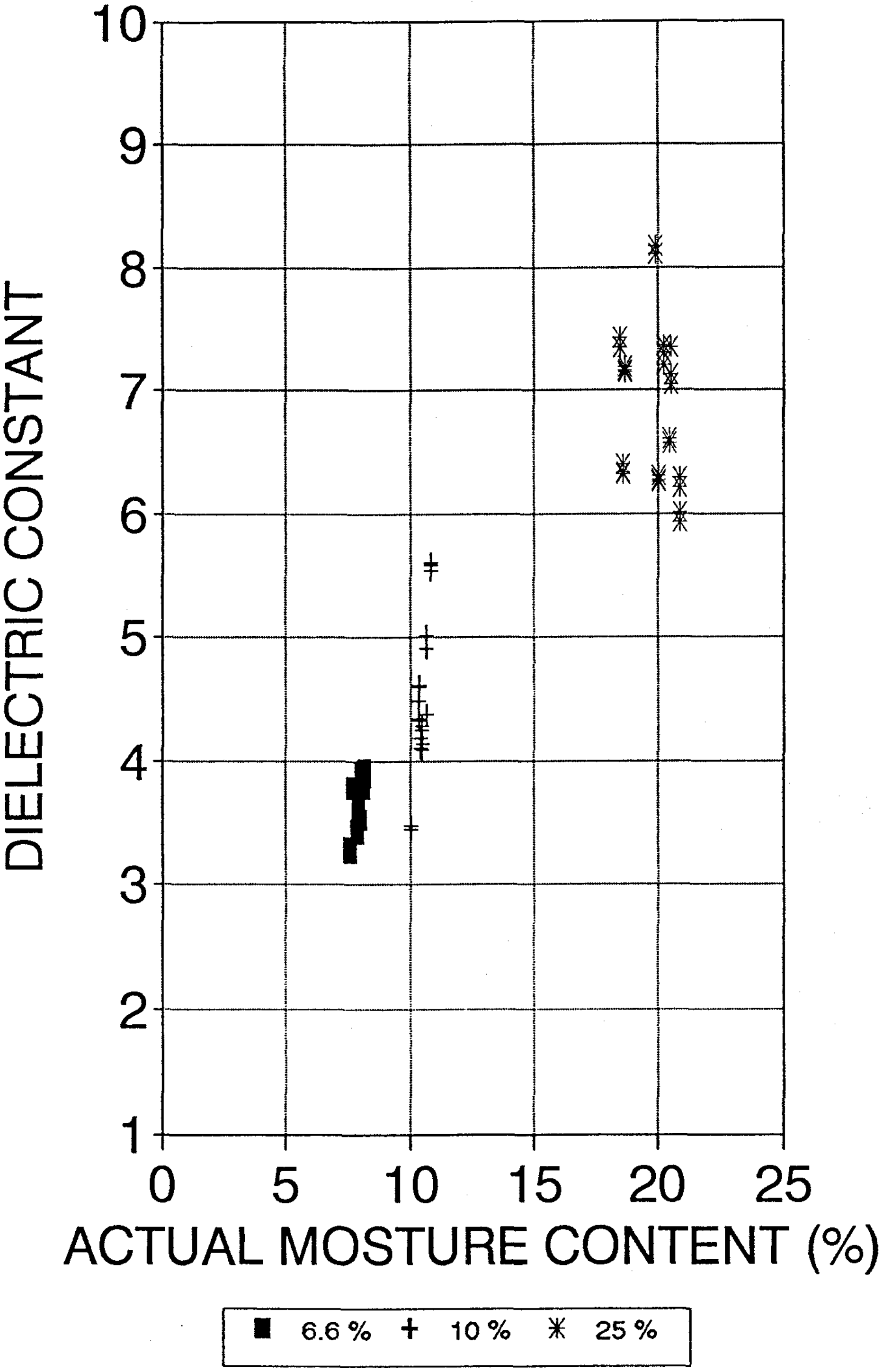

Figure A.4.4. The effect of moisture on the dielectric constant of large tight knots at 1.4 MHz.

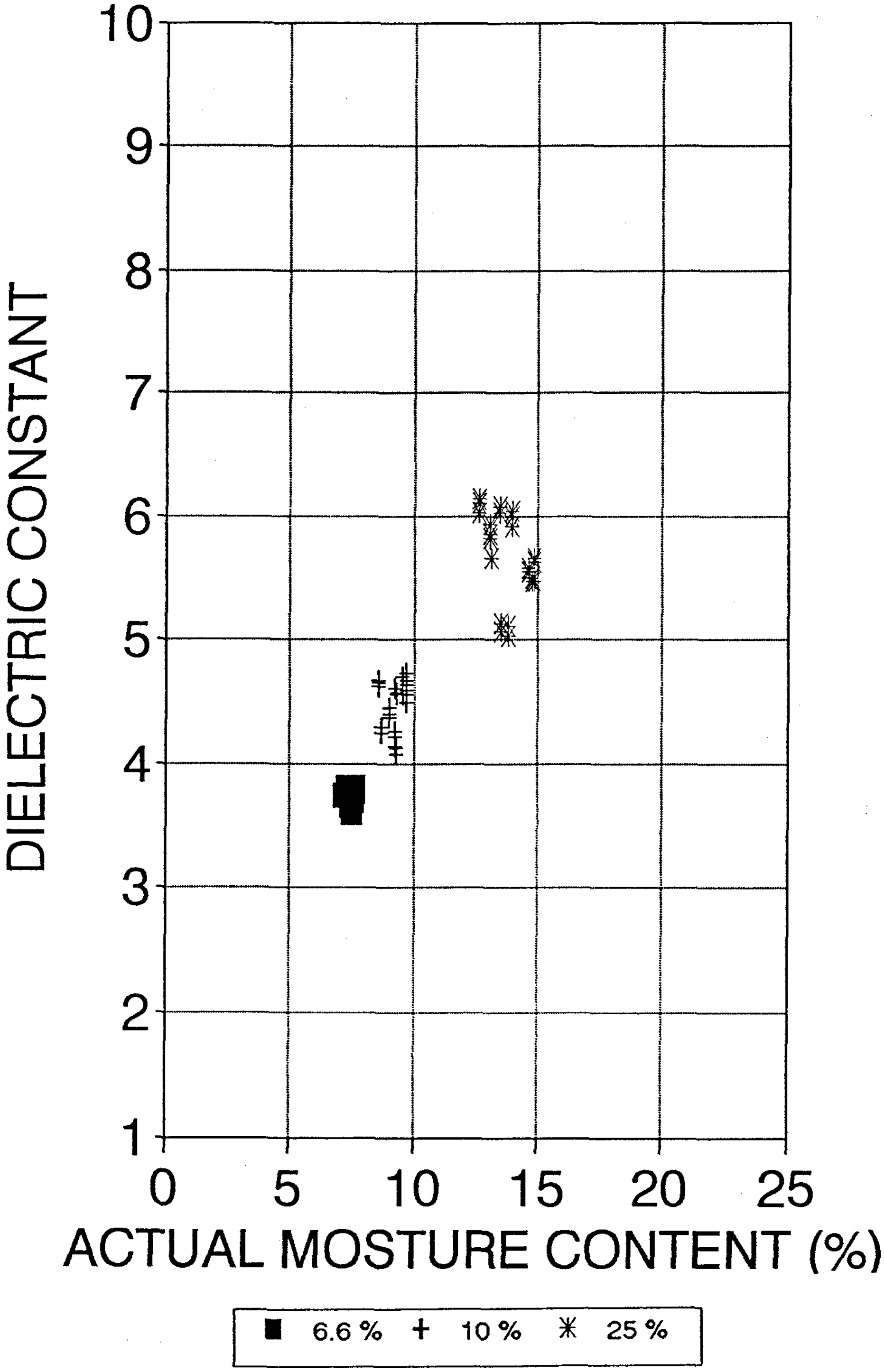

Figure A.4.5. The effect of moisture on the dielectric constant of medium tight knots at 1.4 MHz.

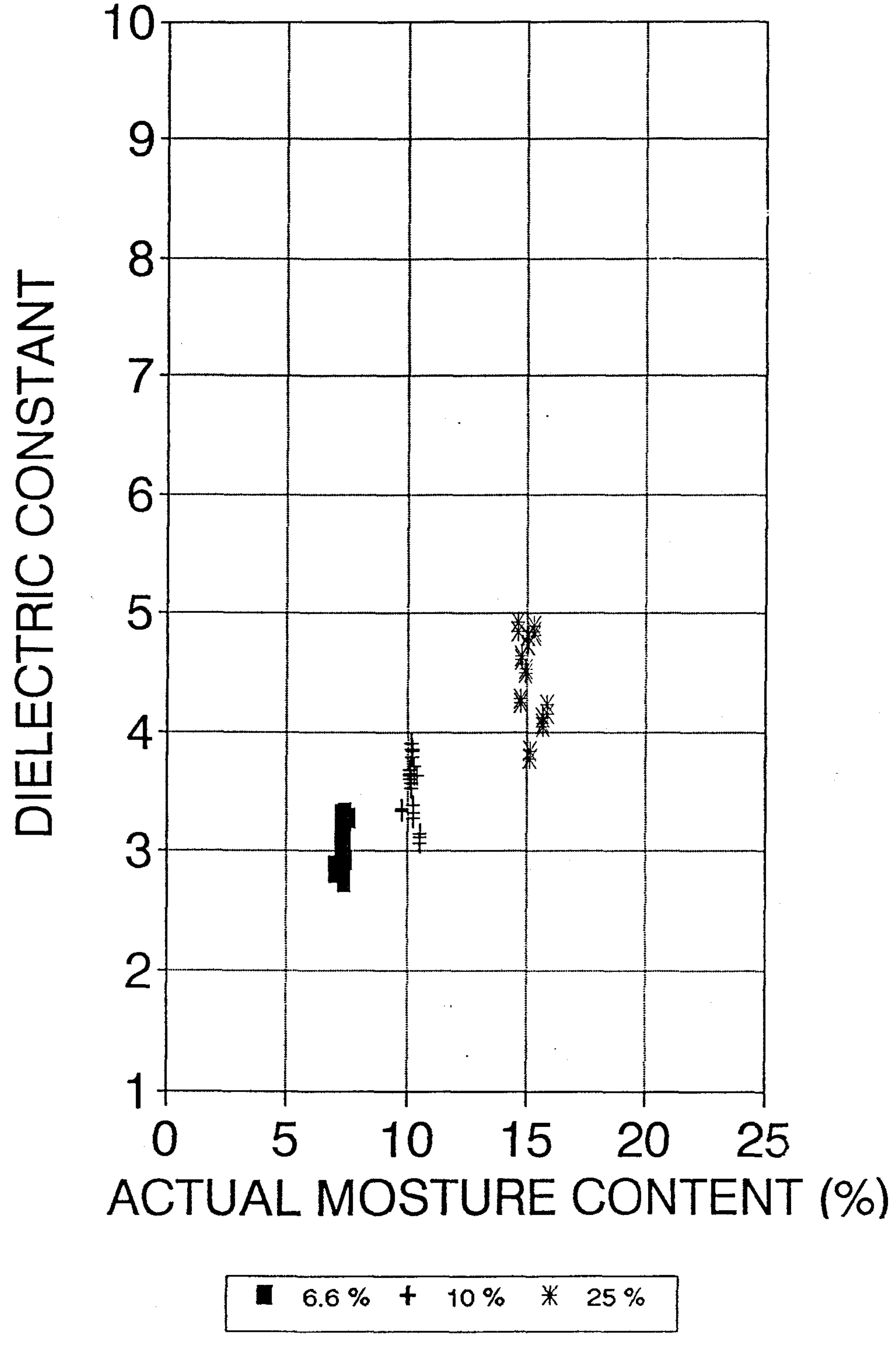

Figure A.4.6. The effect of moisture on the dielectric constant of small tight knots at 1.4 MHz.

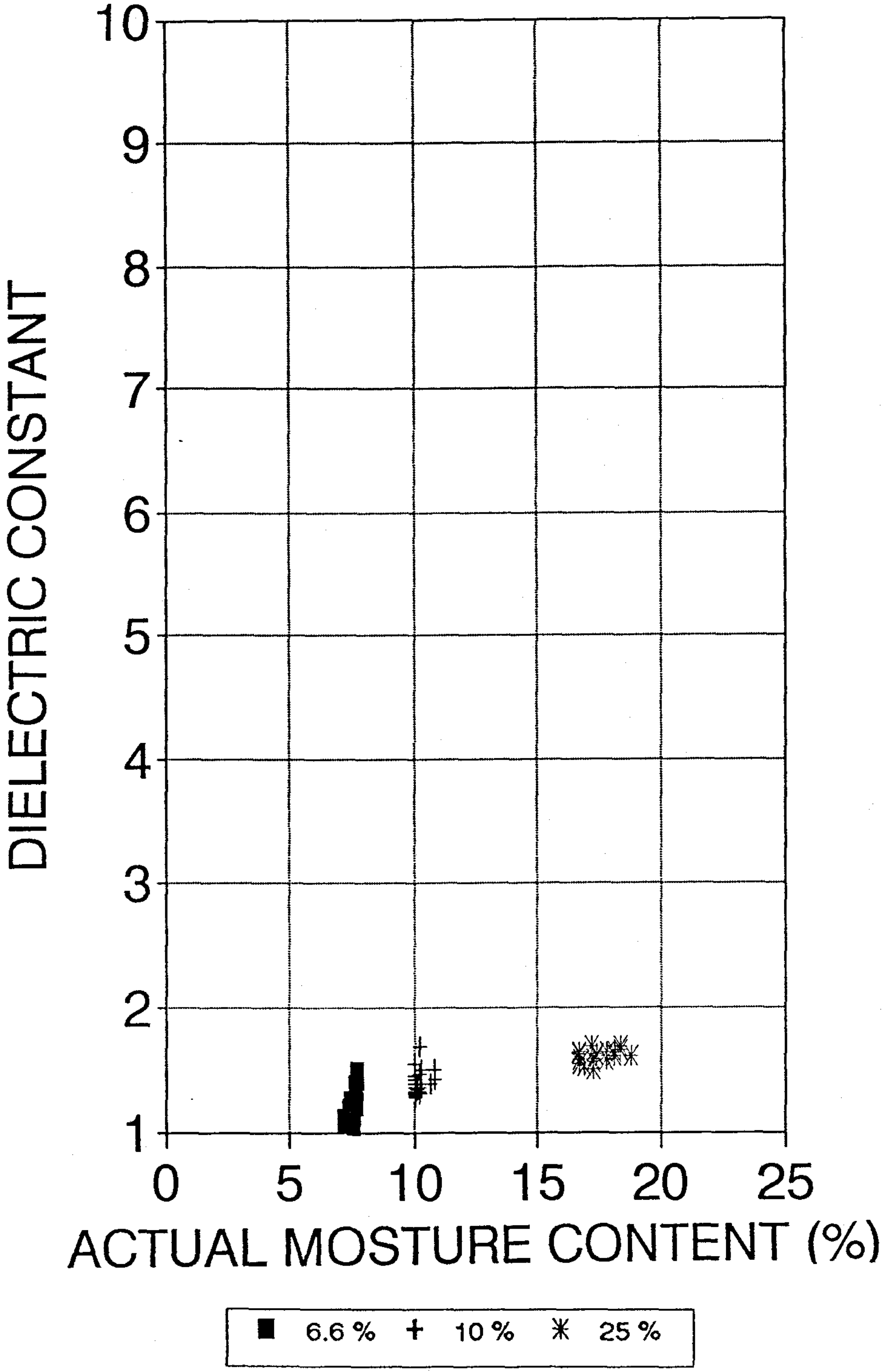

Figure A.4.7. The effect of moisture on the dielectric constant of large open holes at 1.4 MHz.

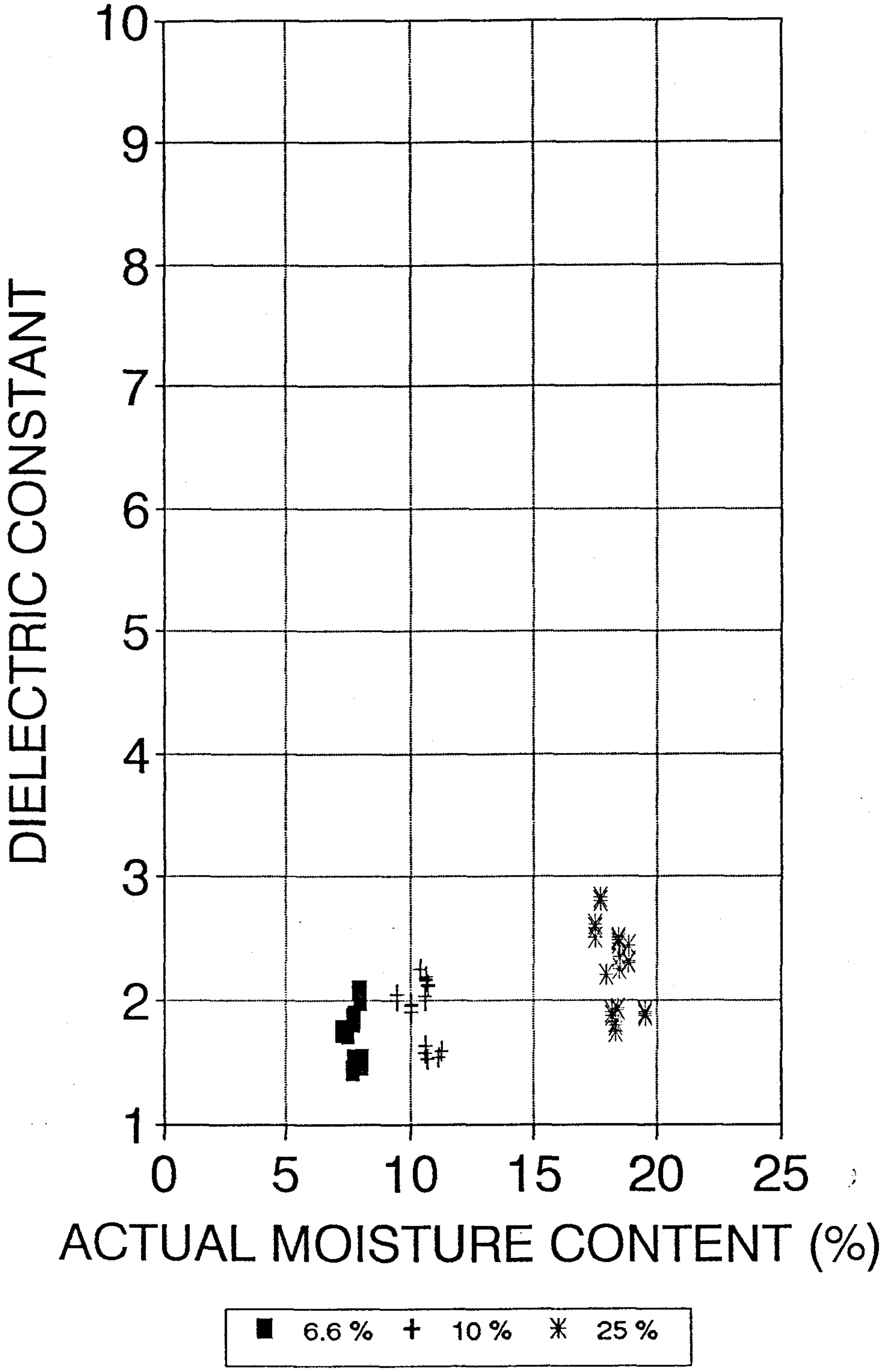

Figure A.4.8. The effect of moisture on the dielectric constant of medium open holes at 1.4 MHz.

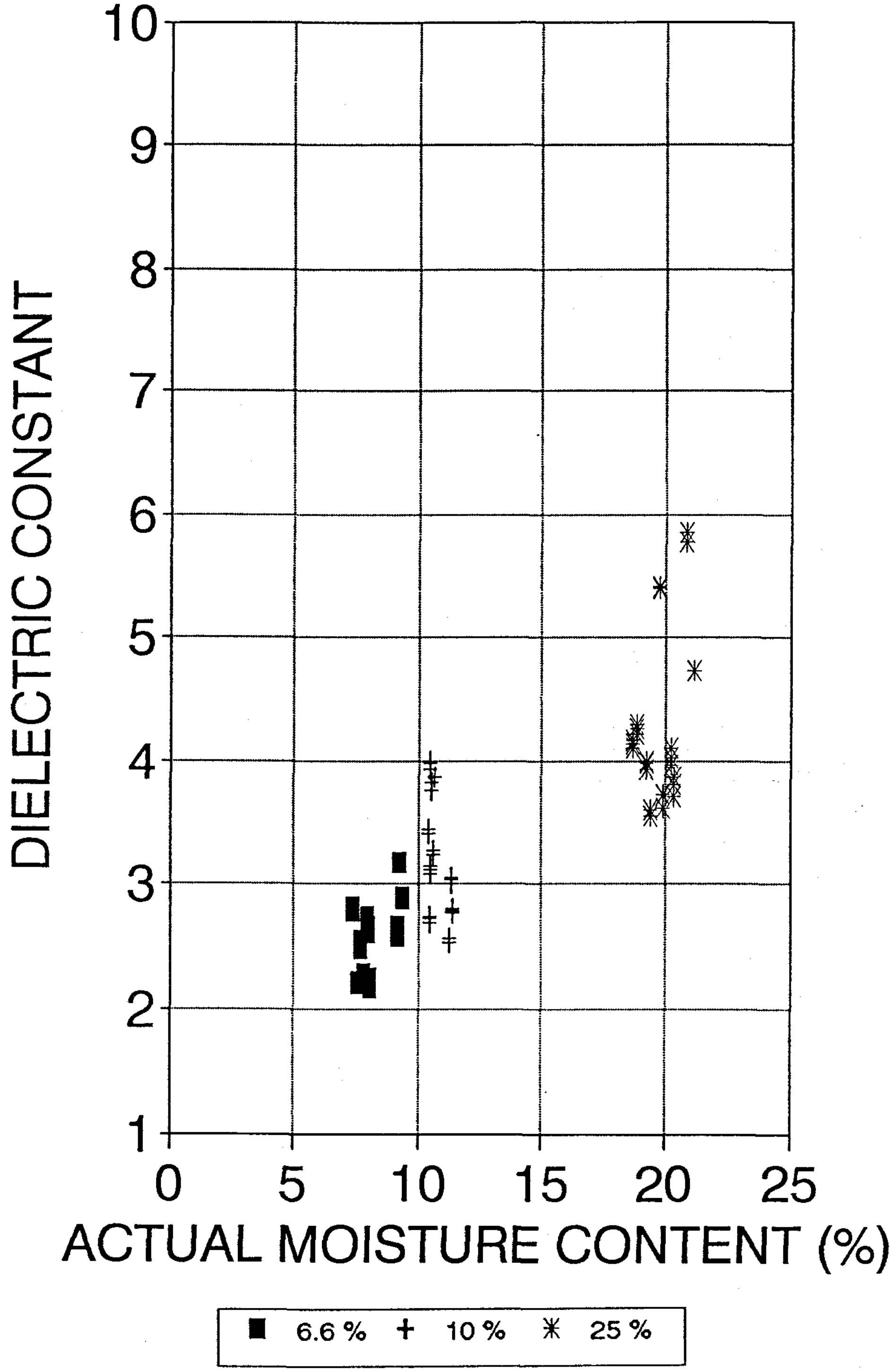

Figure A.4.9. The effect of moisture on the dielectric constant of small open holes at 1.4 MHz.

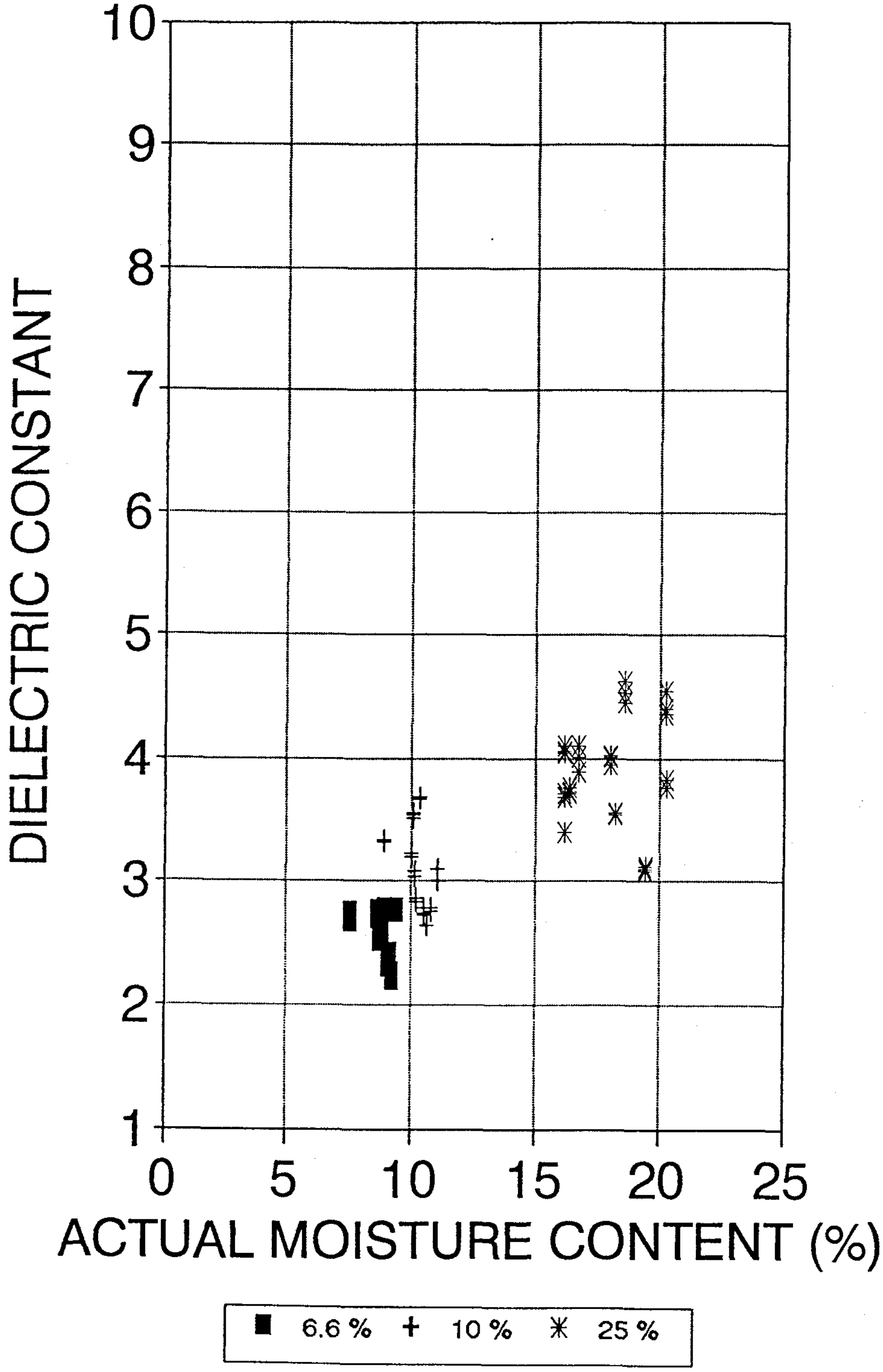

Figure A.4.10. The effect of moisture on the dielectric constant of large pitch pockets at 1.4 MHz.

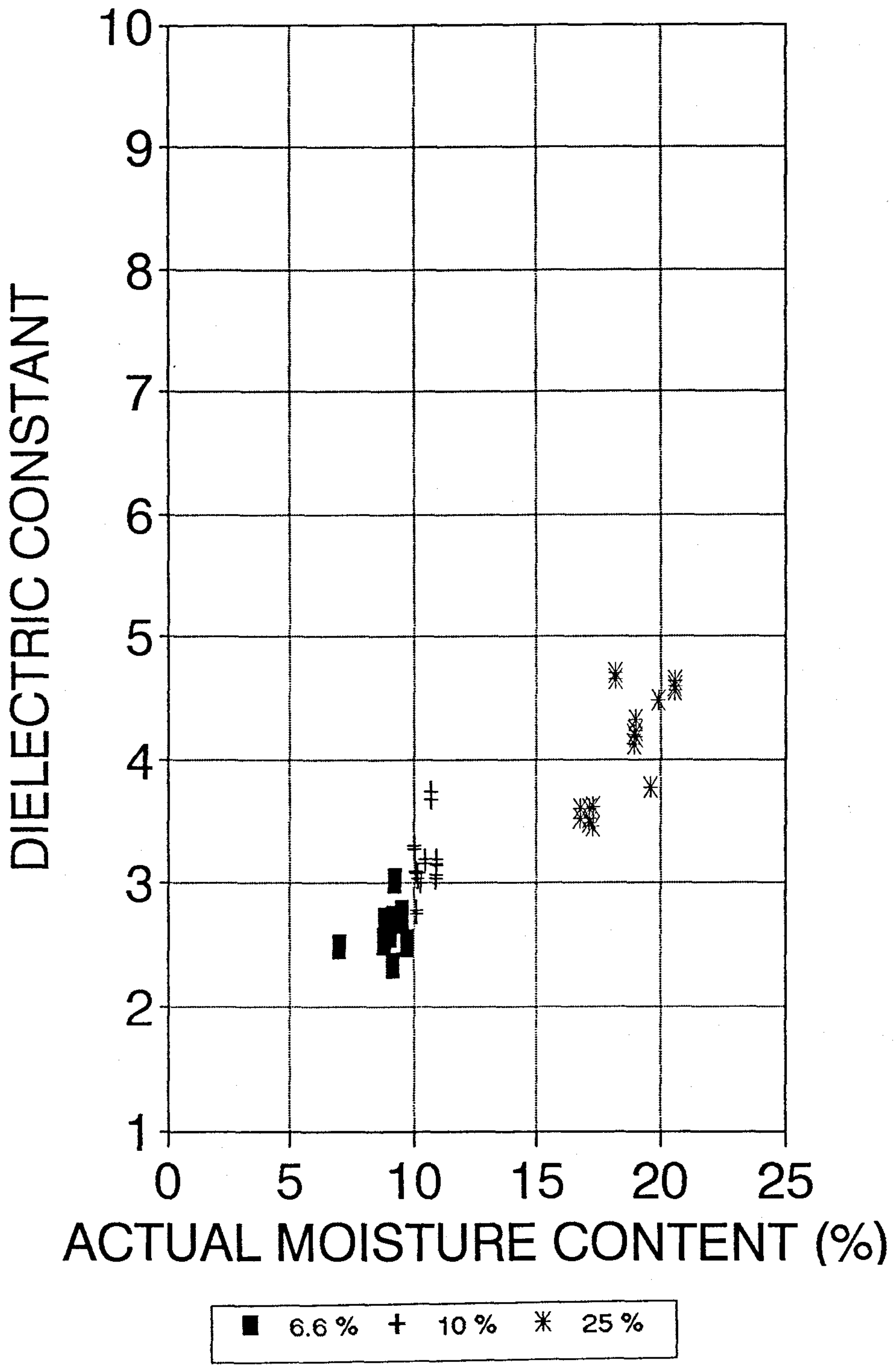

Figure A.4.11. The effect of moisture on the dielectric constant of small pitch pockets at 1.4 MHz.

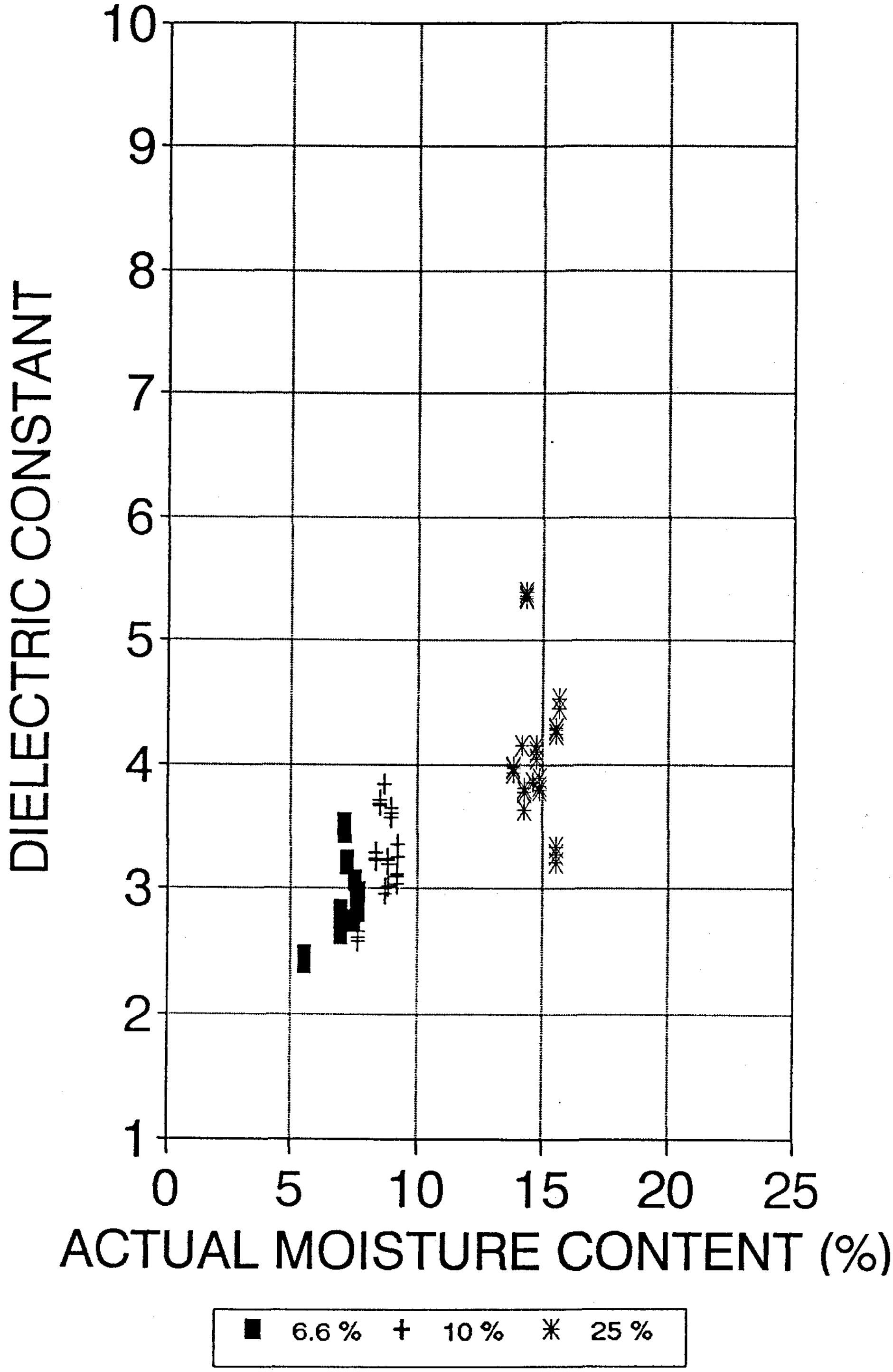

Figure A.4.12. The effect of moisture on the dielectric constant of heavy pitch streaks at 1.4 MHz.

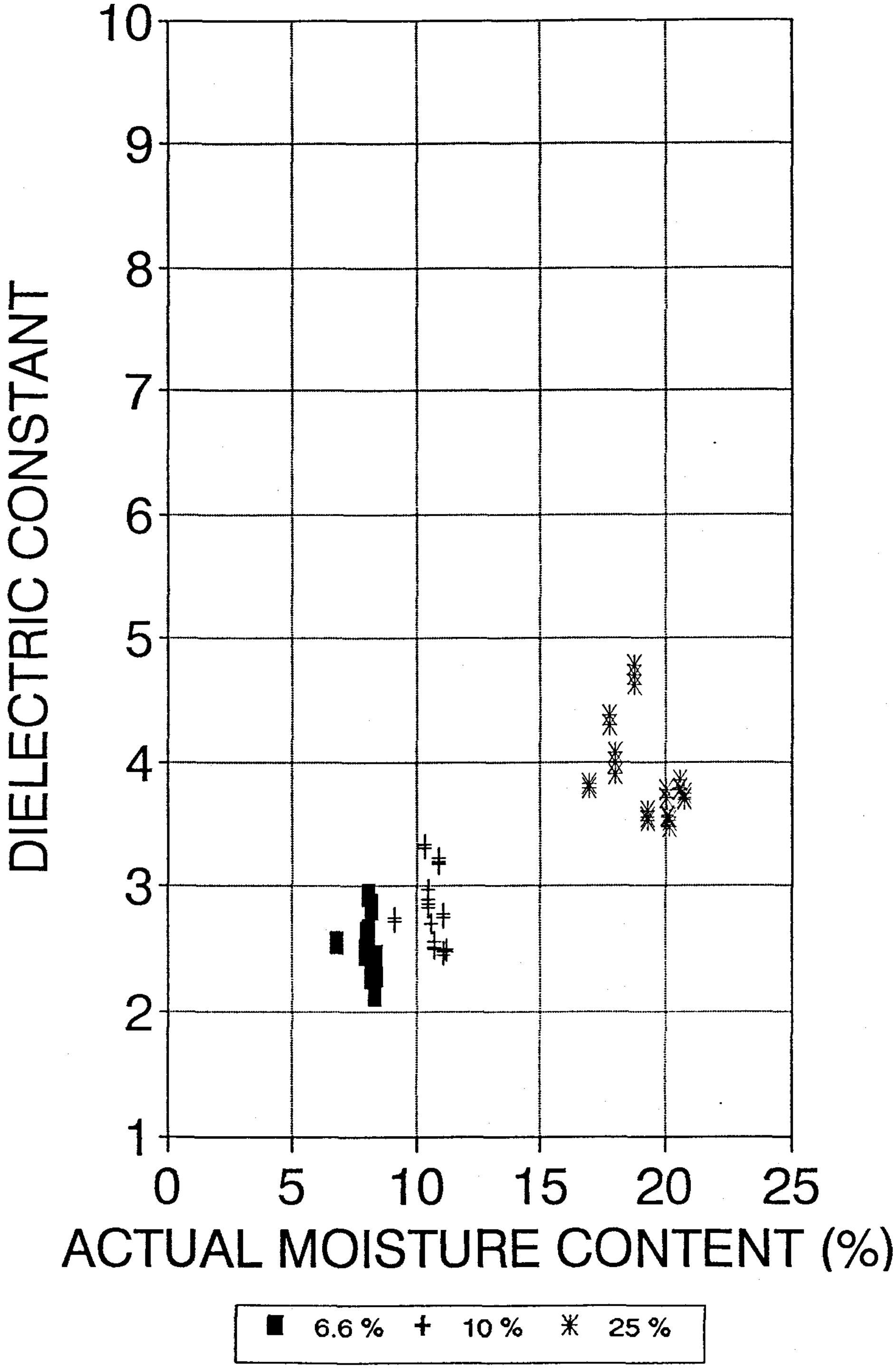

Figure A.4.13. The effect of moisture on the dielectric constant of light pitch streaks at 1.4 MHz.

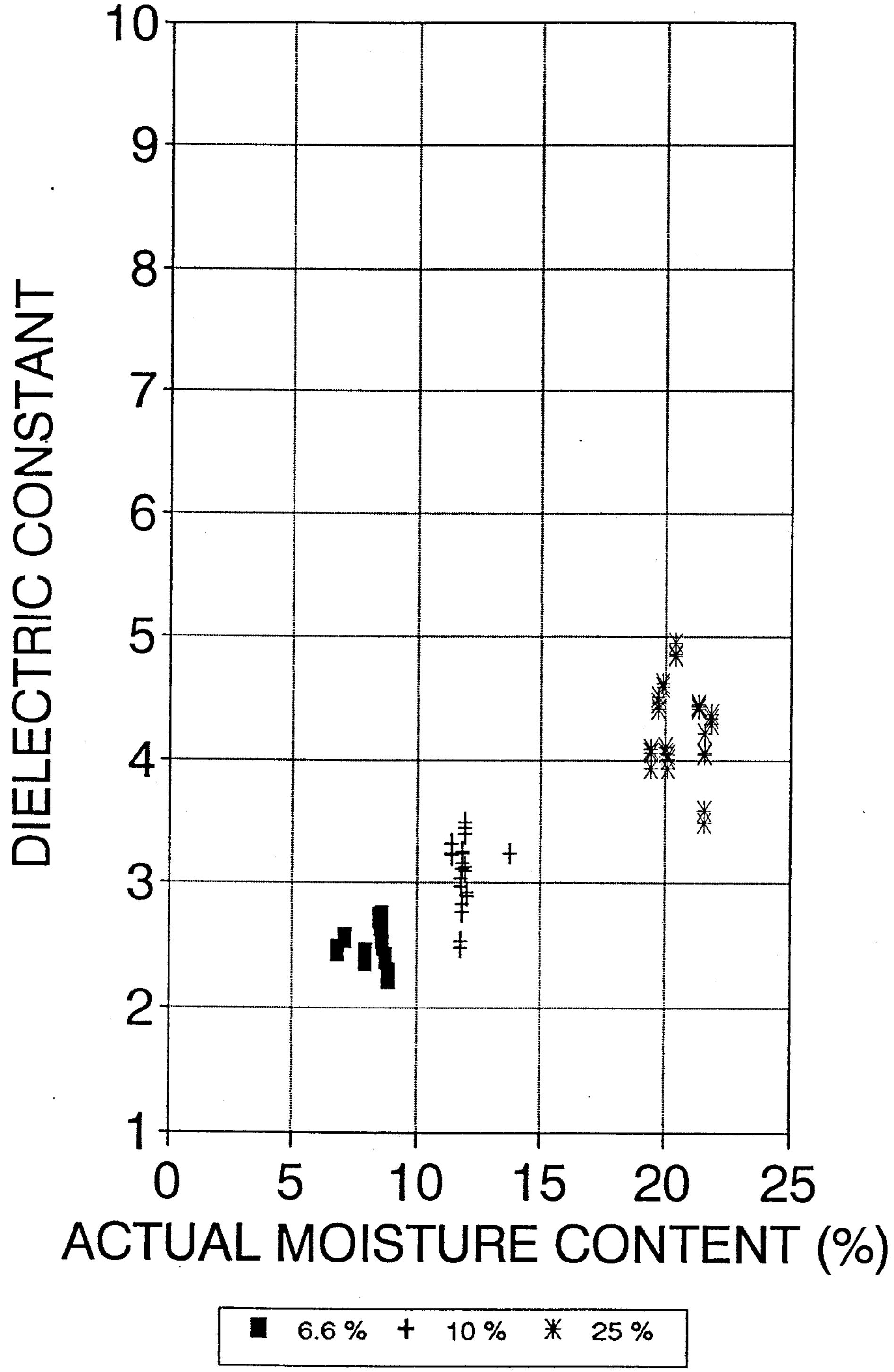

Figure A.4.14. The effect of moisture on the dielectric constant of heavy blue stain at 1.4 MHz.

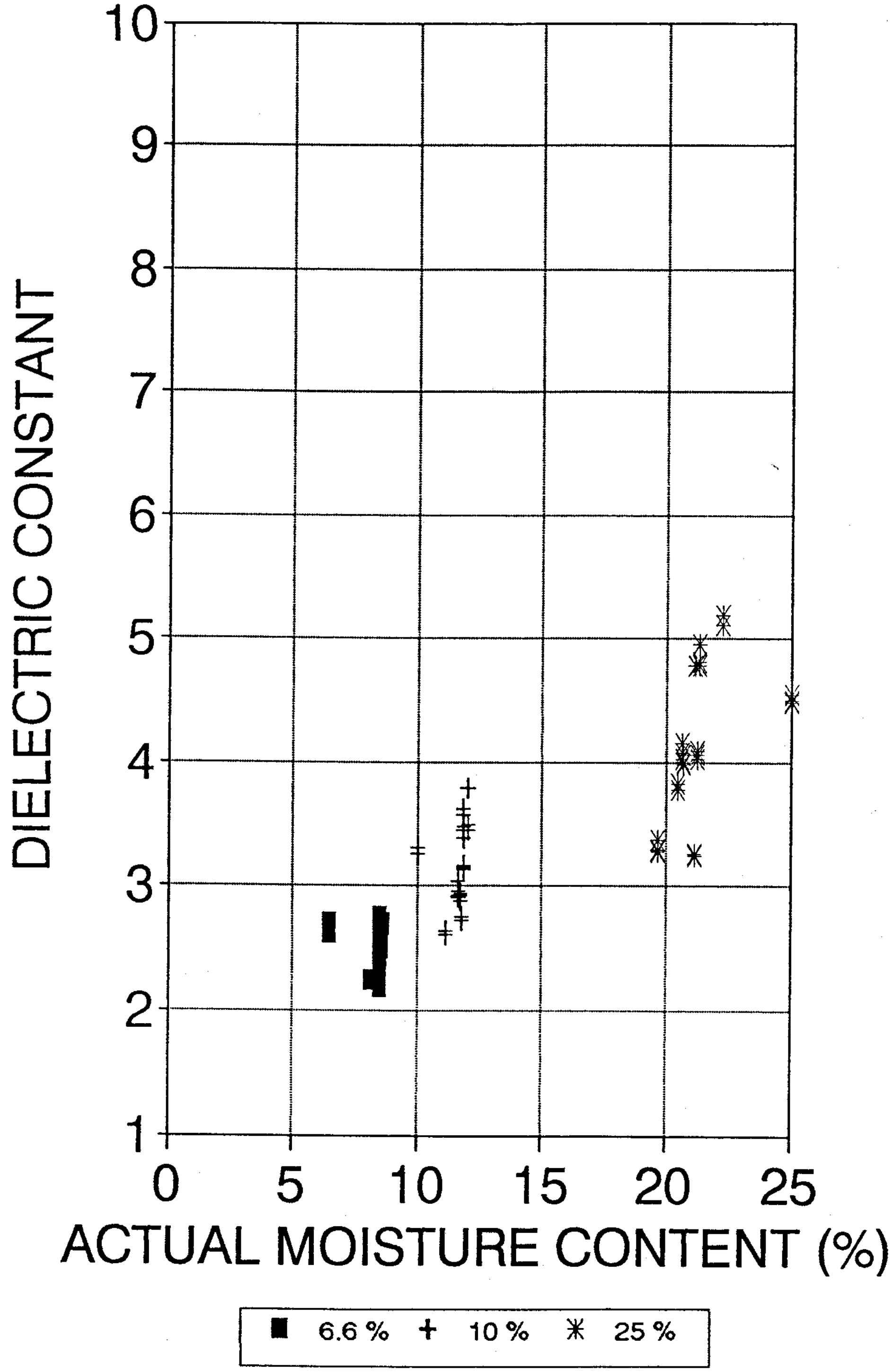

Figure A.4.15. The effect of moisture on the dielectric constant of light blue stain at 1.4 MHz.

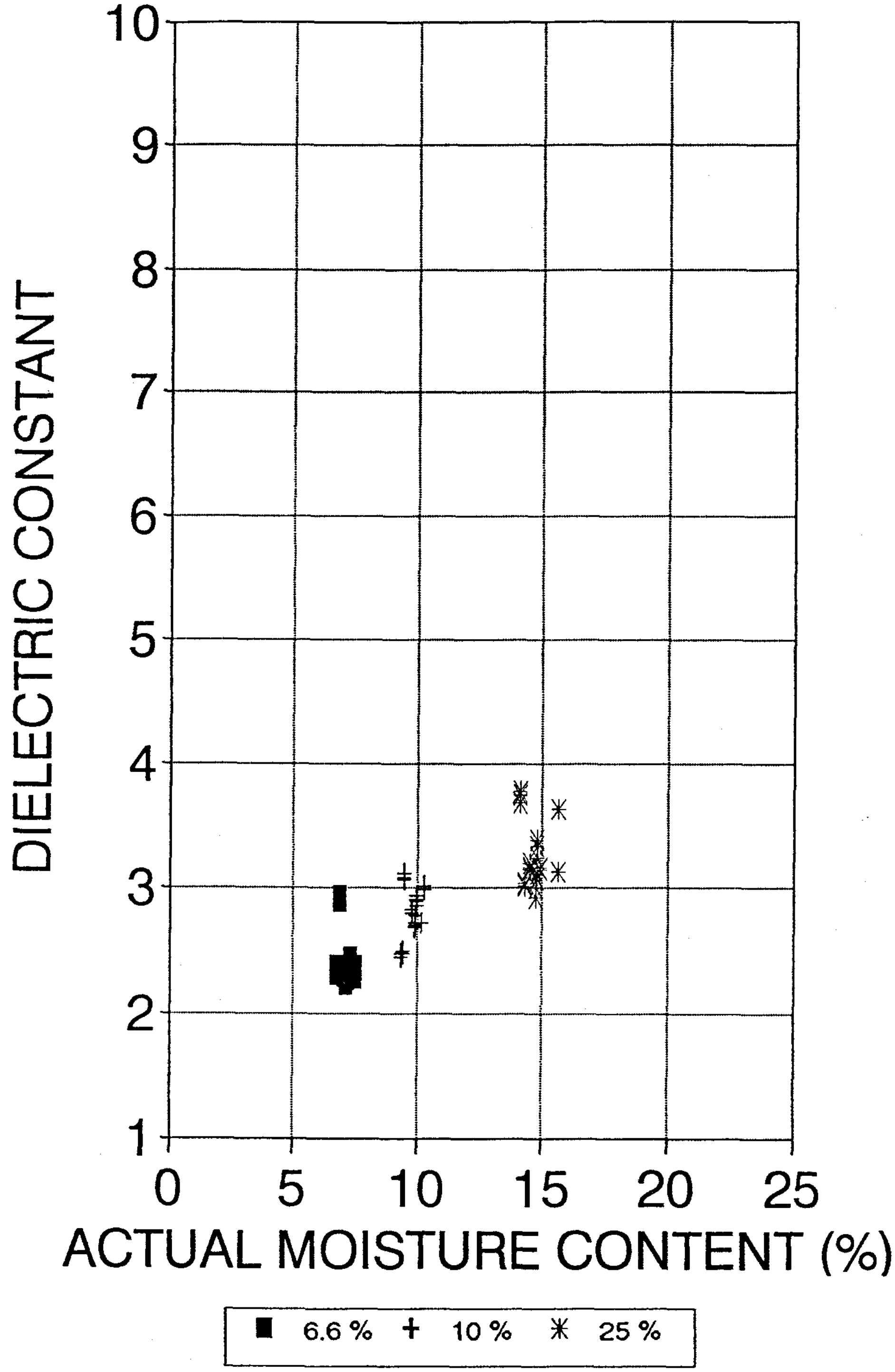

Figure A.4.16. The effect of moisture on the dielectric constant of clearwood at 1.4 MHz.

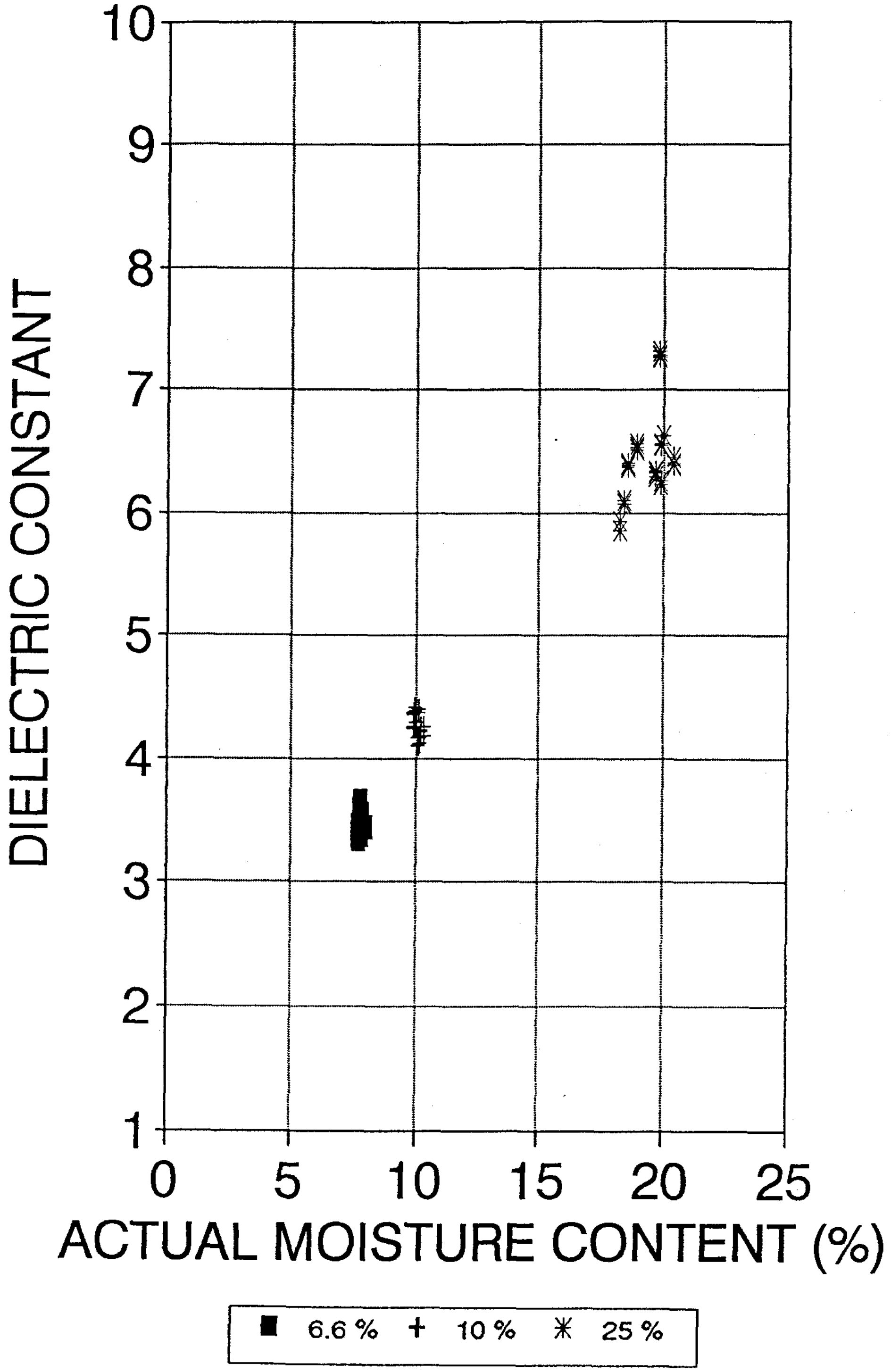

Figure A.4.17. The effect of moisture on the dielectric constant of large loose knots at 10 MHz.

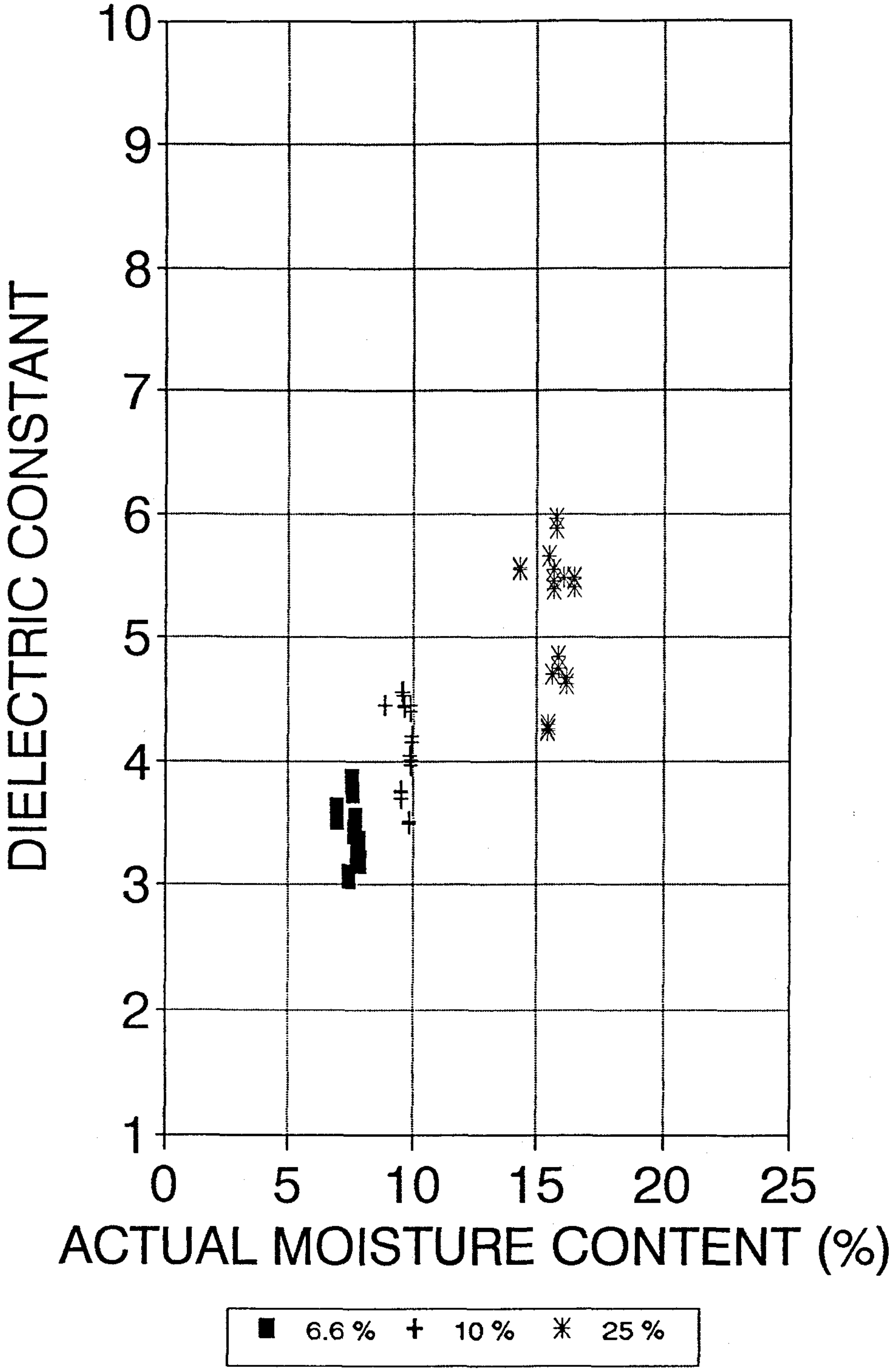

Figure A.4.18. The effect of moisture on the dielectric constant of medium loose knots at 10 MHz.

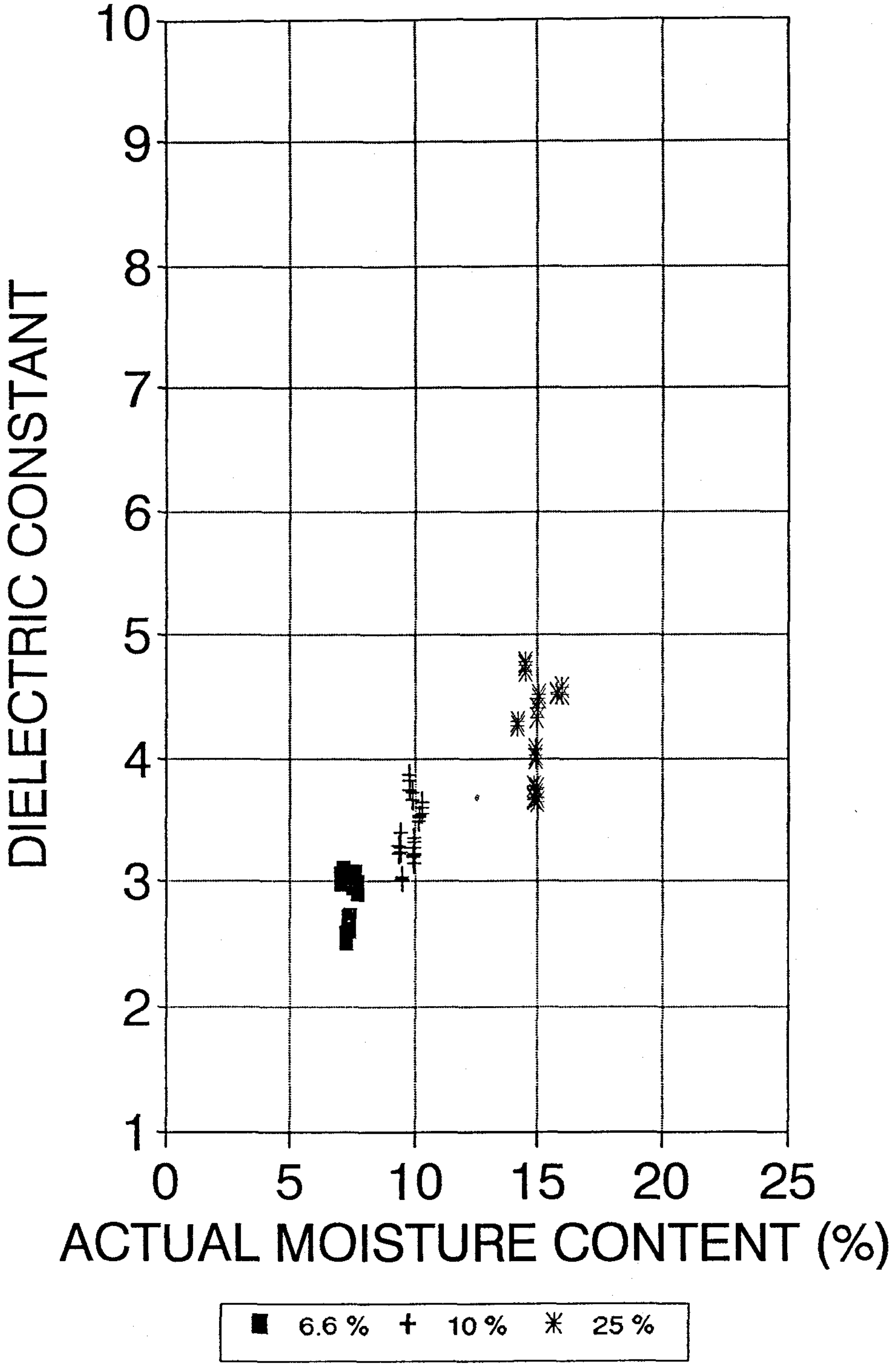

Figure A.4.19. The effect of moisture on the dielectric constant of small loose knots at 10 MHz.

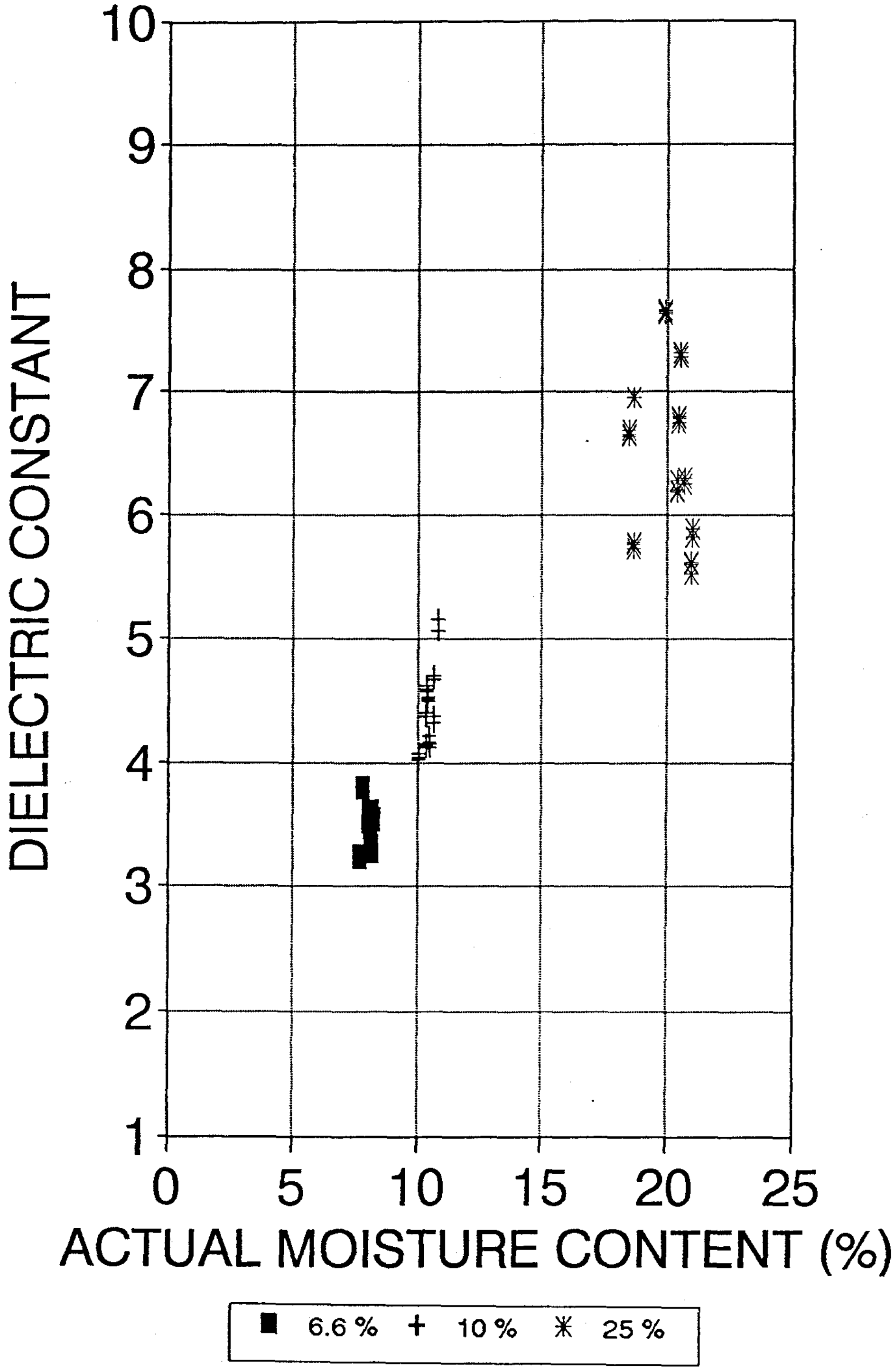

Figure A.4.20. The effect of moisture on the dielectric constant of large tight knots at 10 MHz.

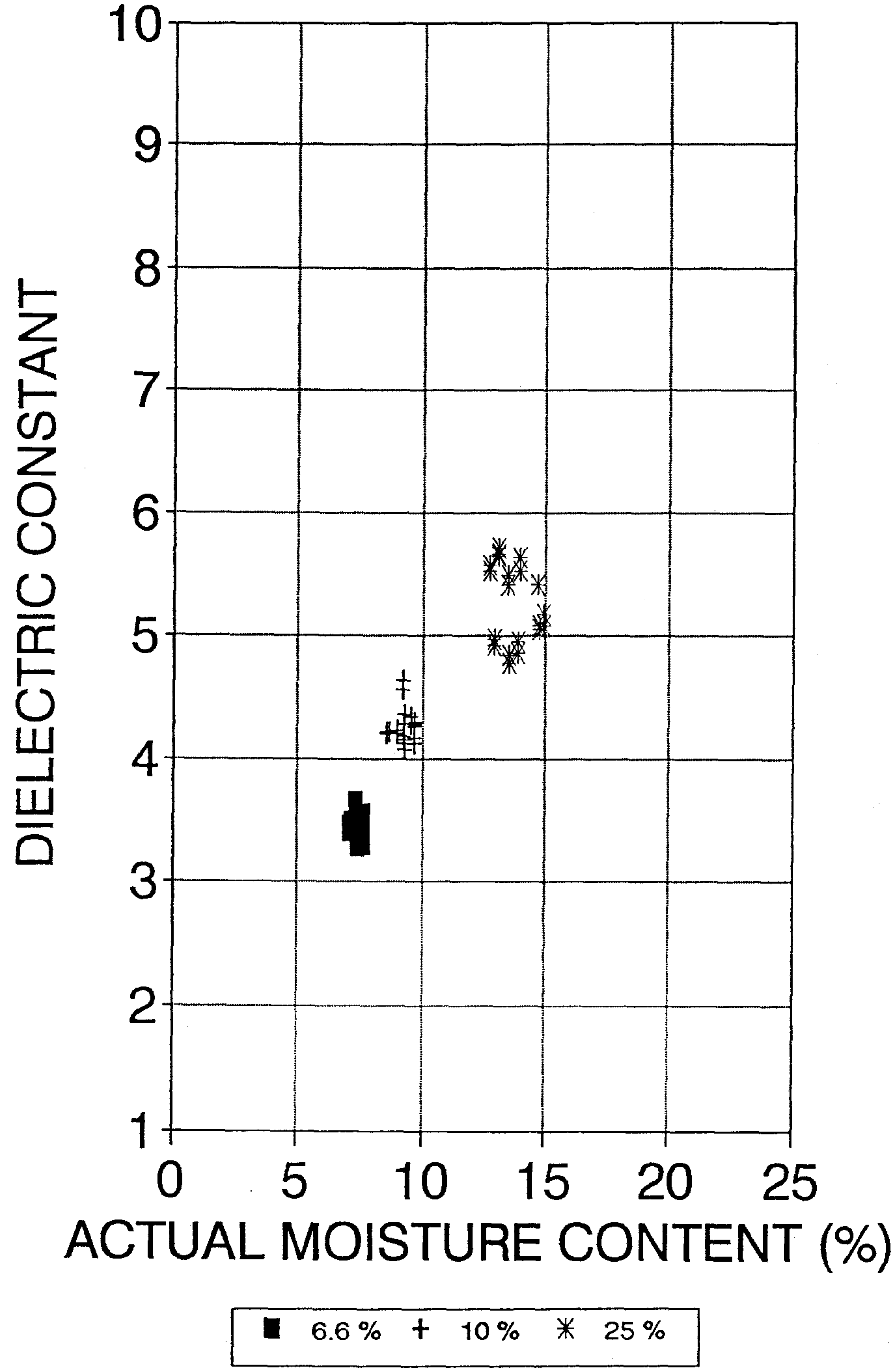

Figure A.4.21. The effect of moisture on the dielectric constant of medium tight knots at 10 MHz.

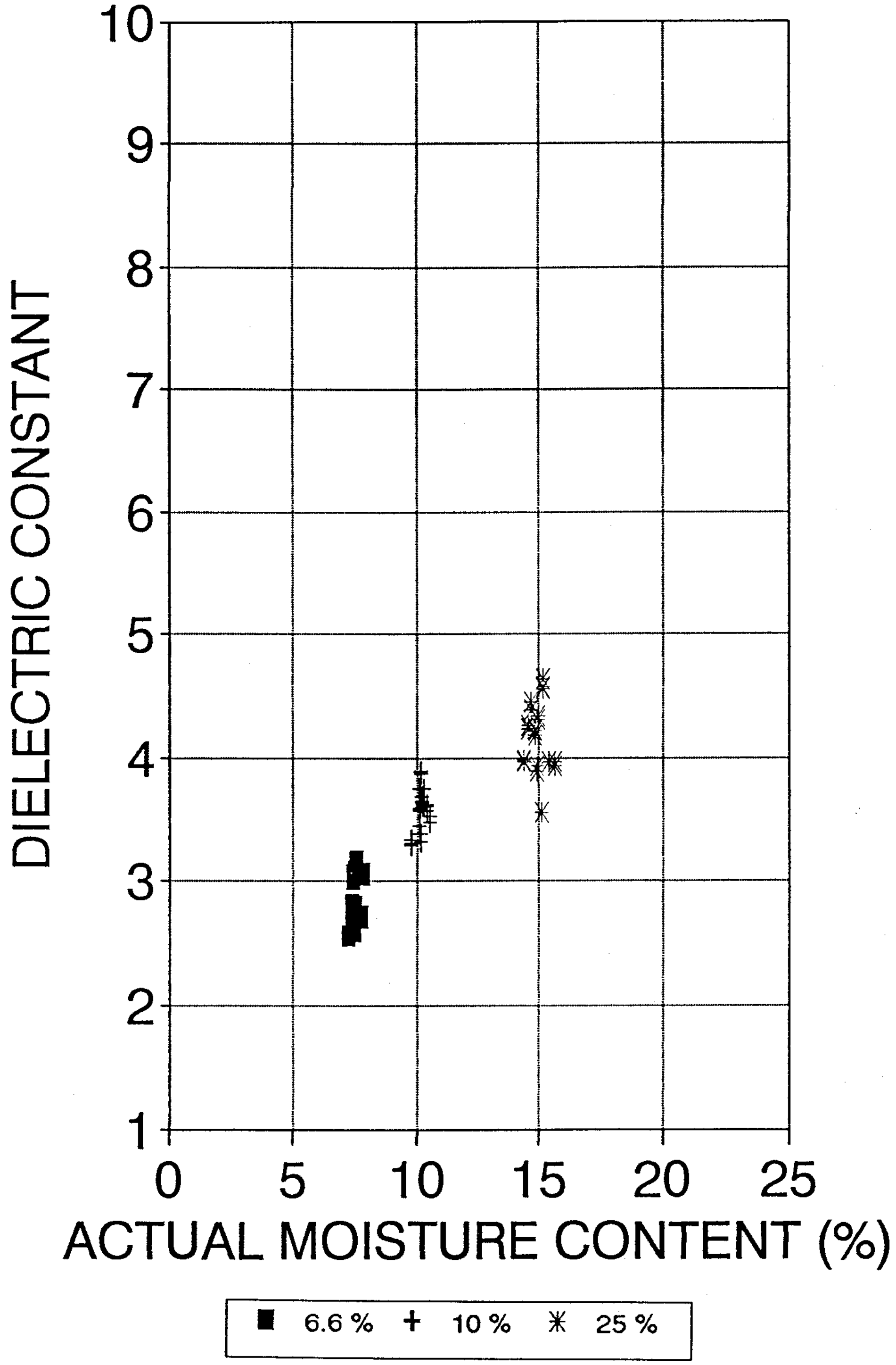

Figure A.4.22. The effect of moisture on the dielectric constant of small tight knots at 10 MHz.

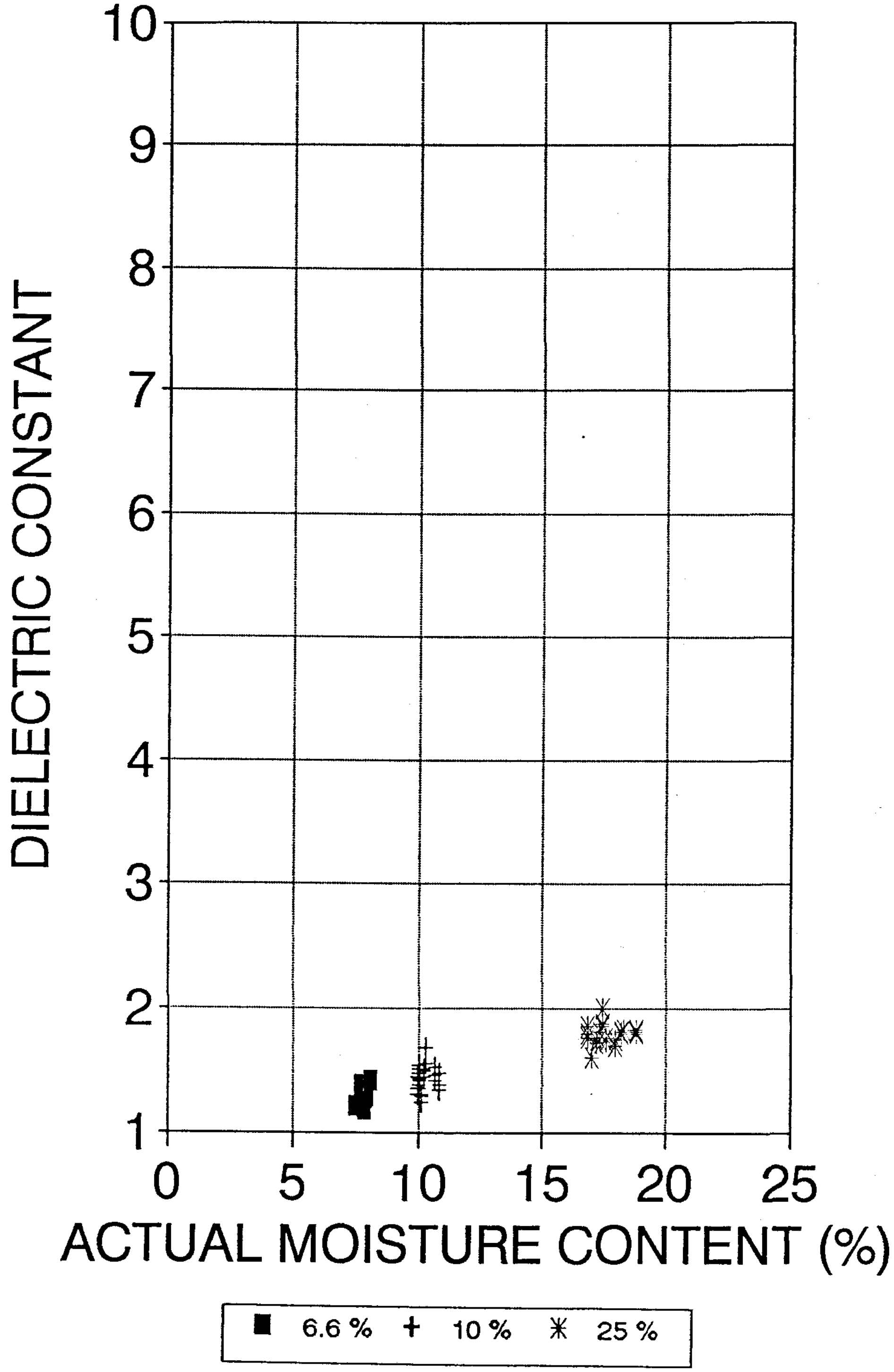

Figure A.4.23. The effect of moisture on the dielectric constant of large open holes at 10 MHz.

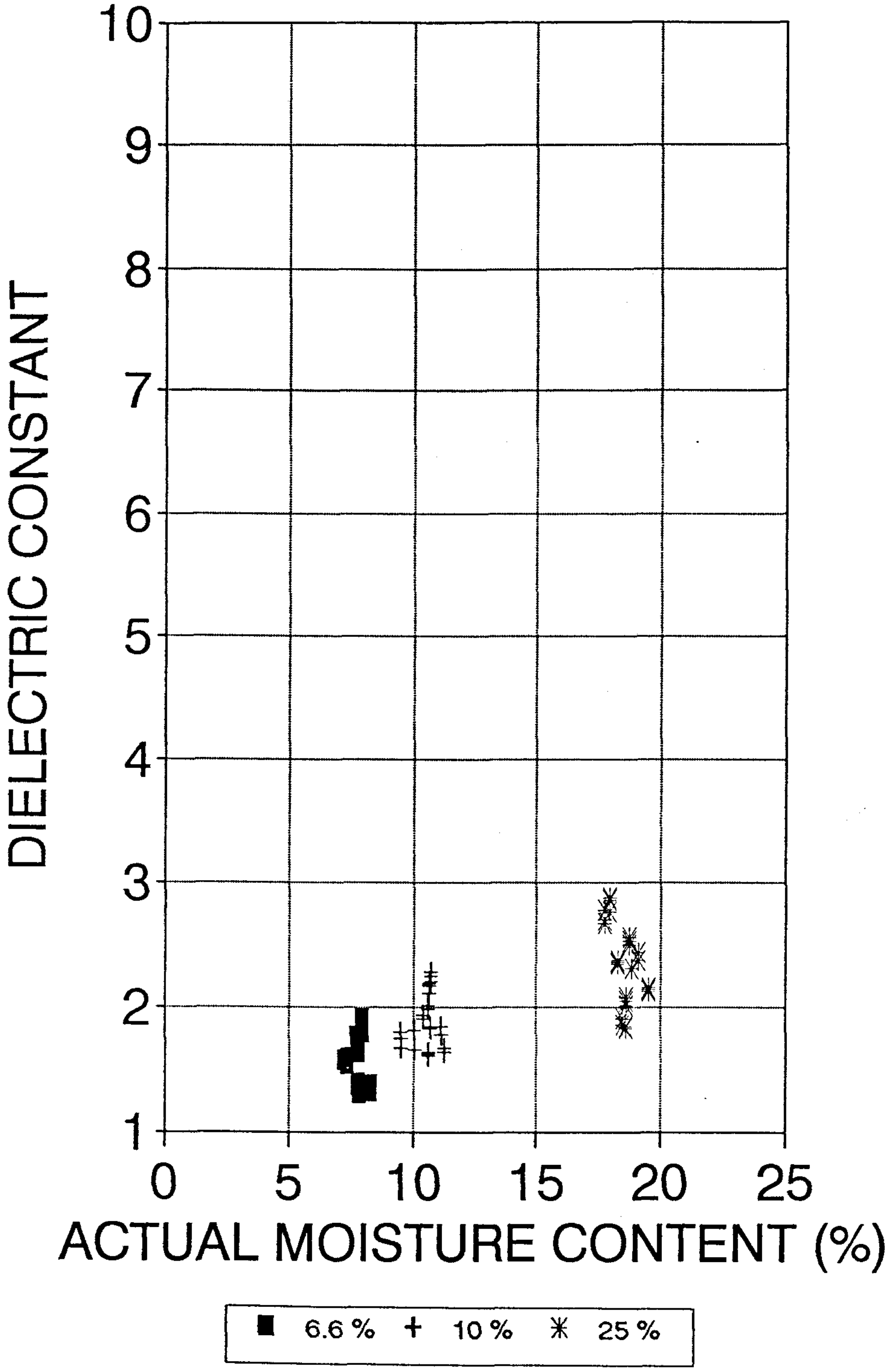

Figure A.4.24. The effect of moisture on the dielectric constant of medium open holes at 10 MHz.

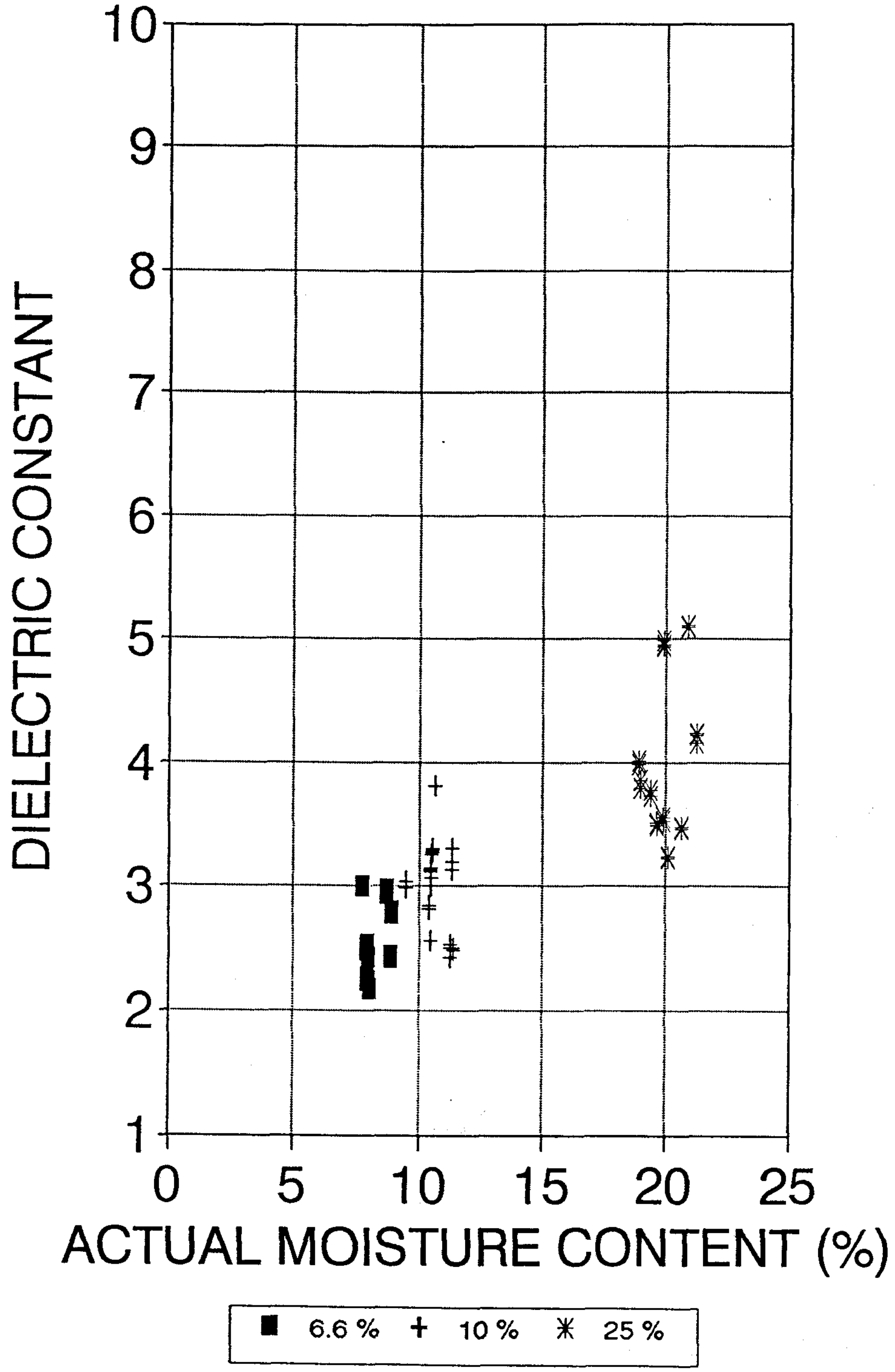

Figure A.4.25. The effect of moisture on the dielectric constant of small open holes at 10 MHz.

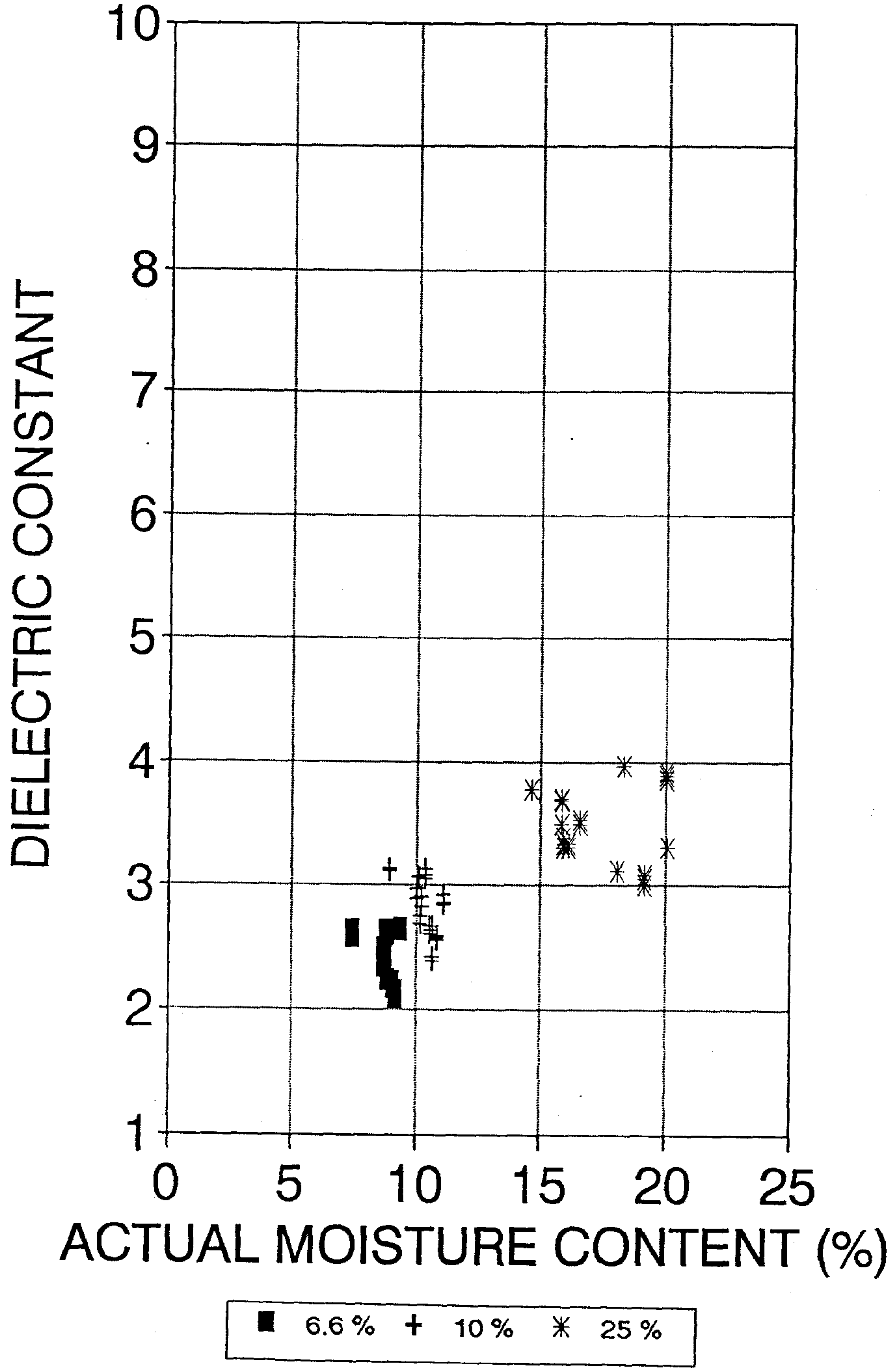

Figure A.4.26. The effect of moisture on the dielectric constant of large pitch pockets at 10 MHz.

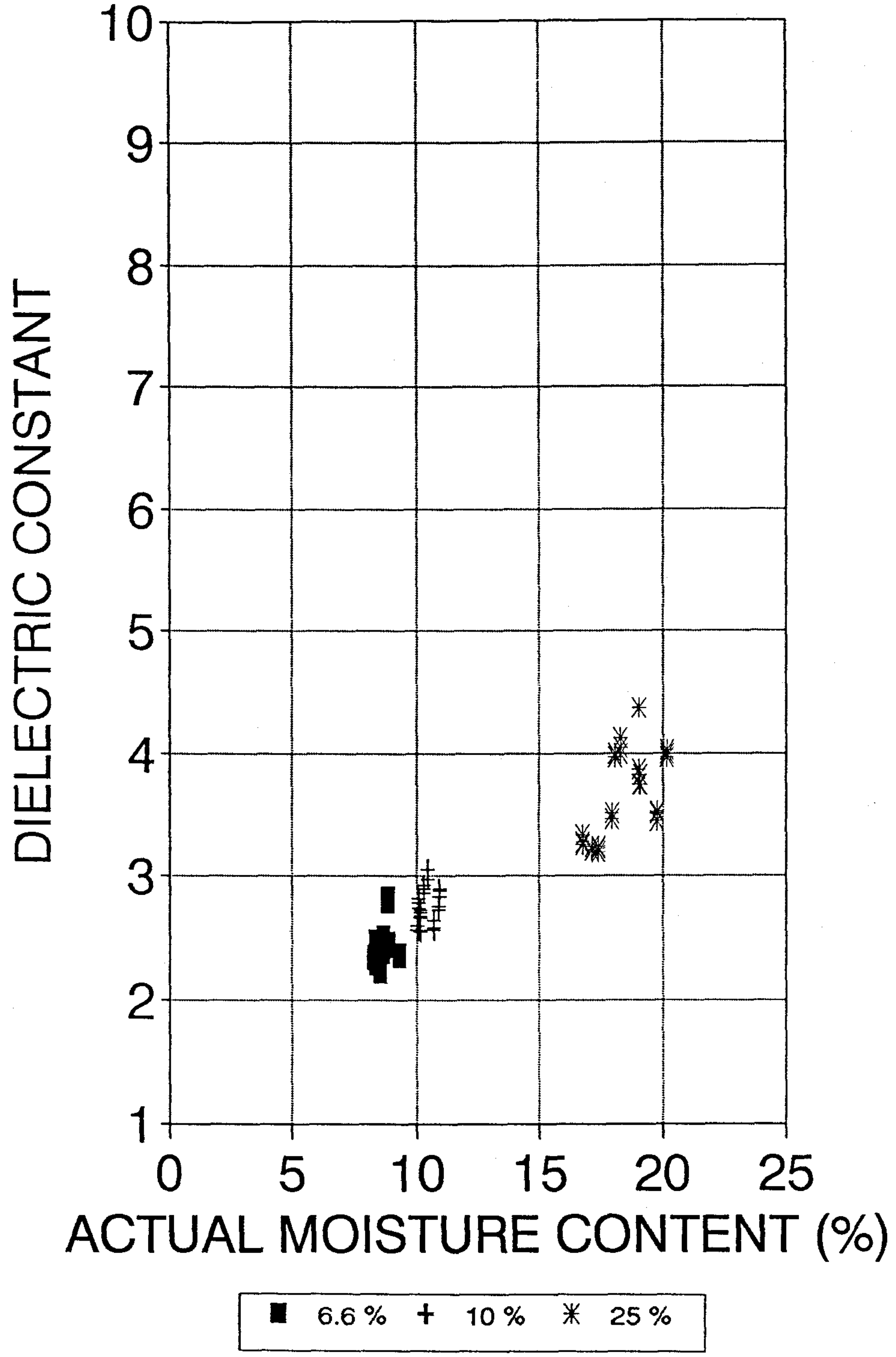

Figure A.4.27. The effect of moisture on the dielectric constant of small pitch pockets at 10 MHz.

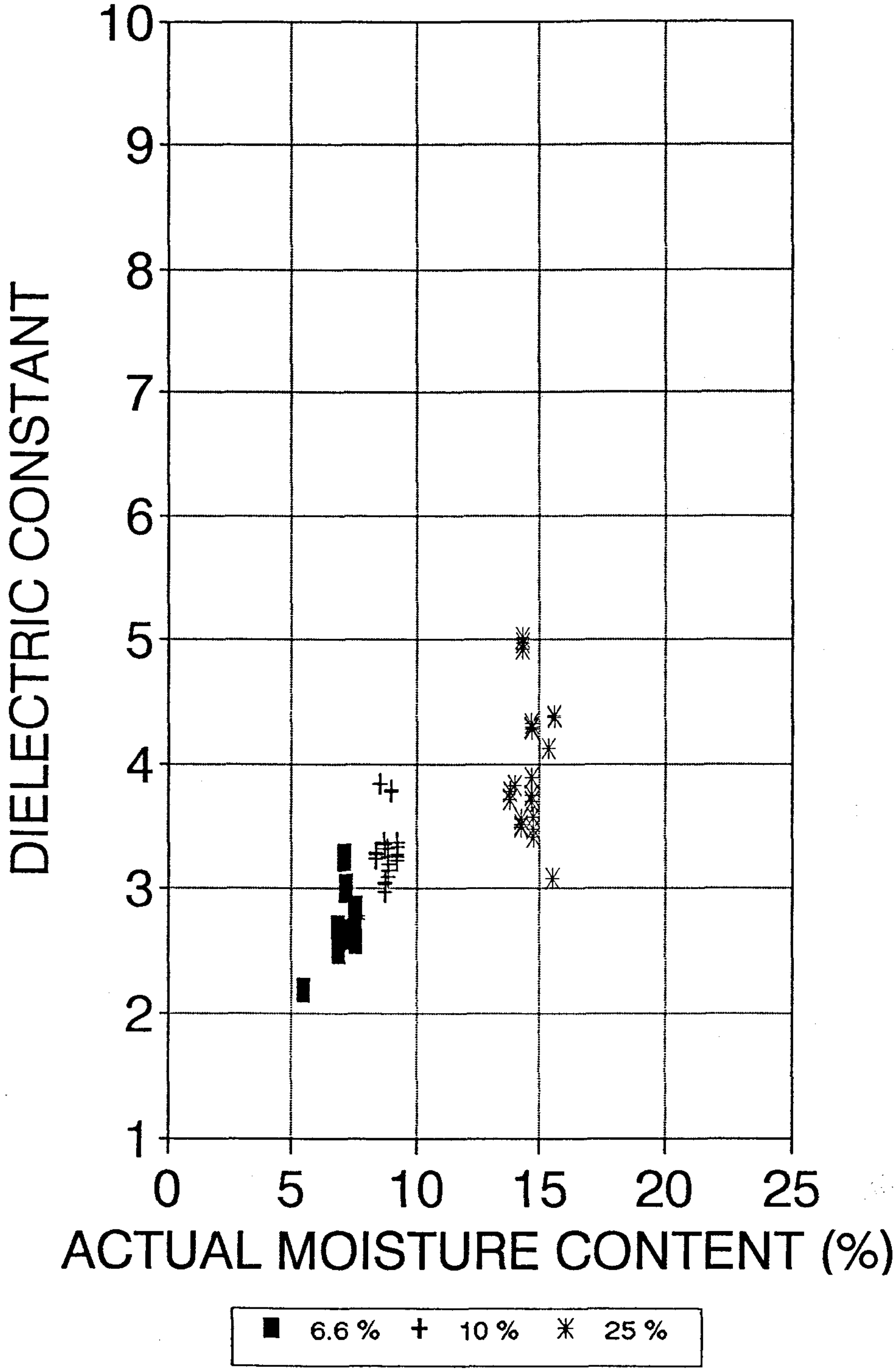

Figure A.4.28. The effect of moisture on the dielectric constant of heavy pitch streaks at 10 MHz.

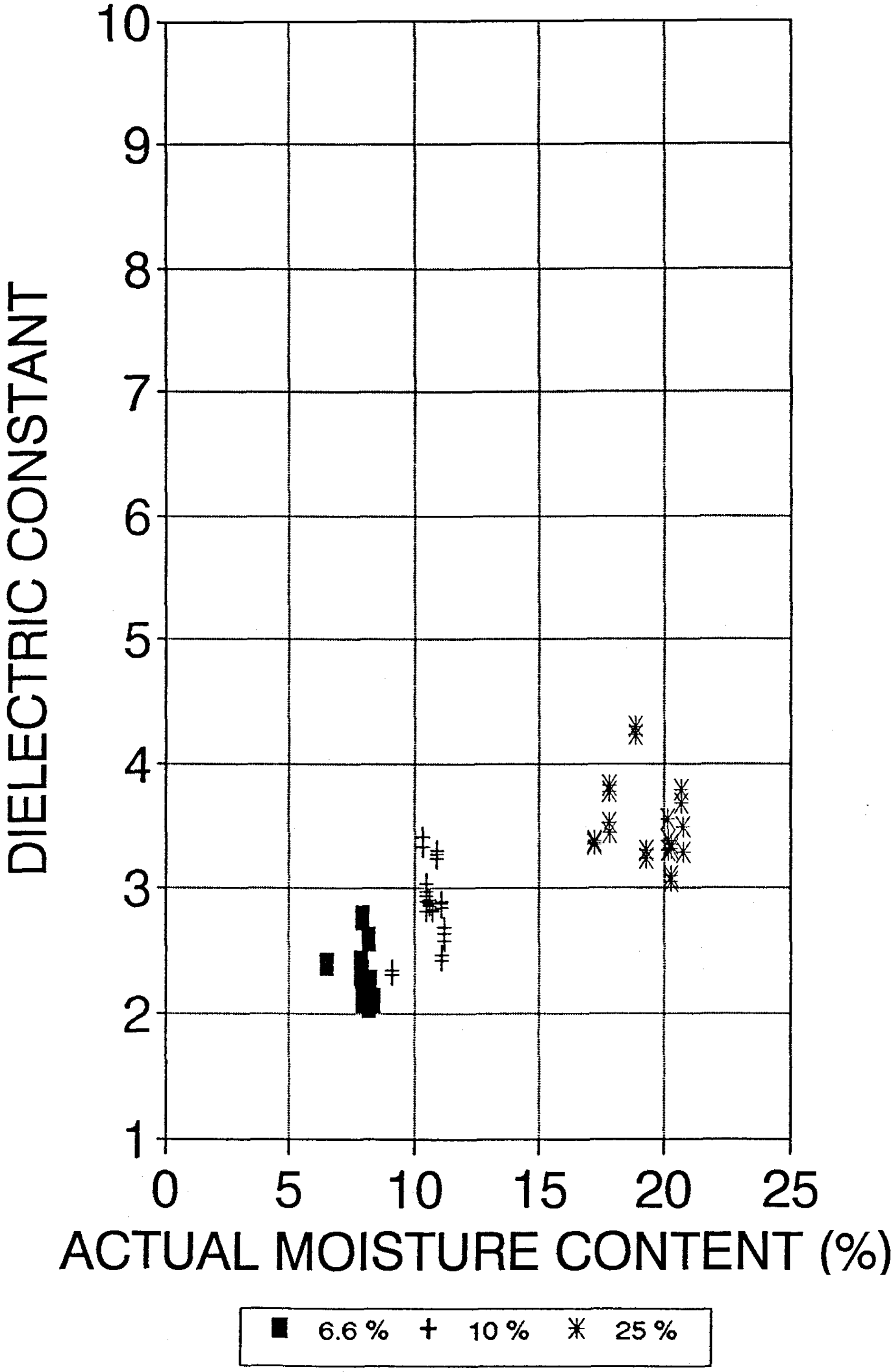

Figure A.4.29. The effect of moisture on the dielectric constant of light pitch streaks at 10 MHz.

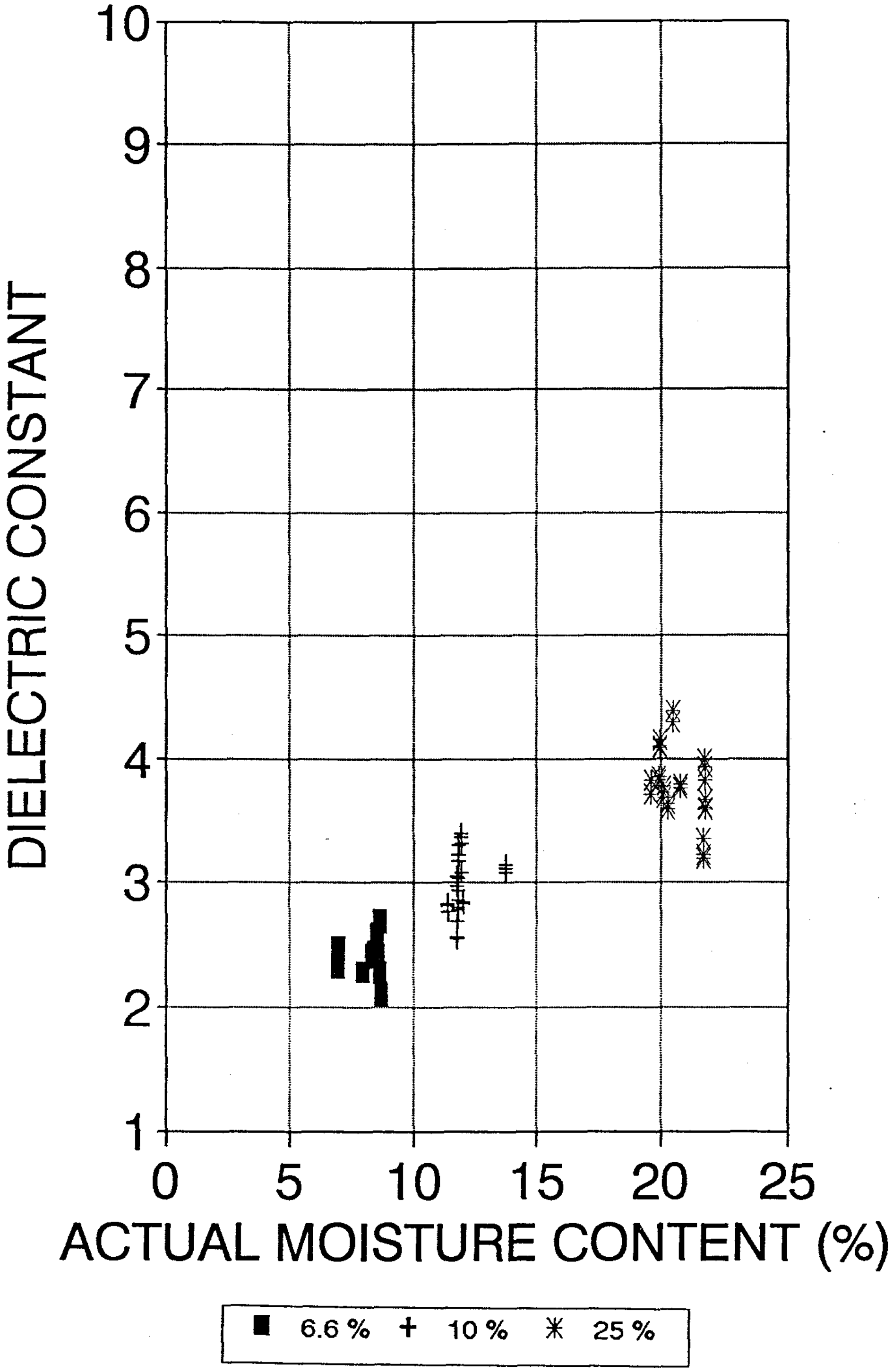

Figure A.4.30. The effect of moisture on the dielectric constant of heavy blue stain at 10 MHz.

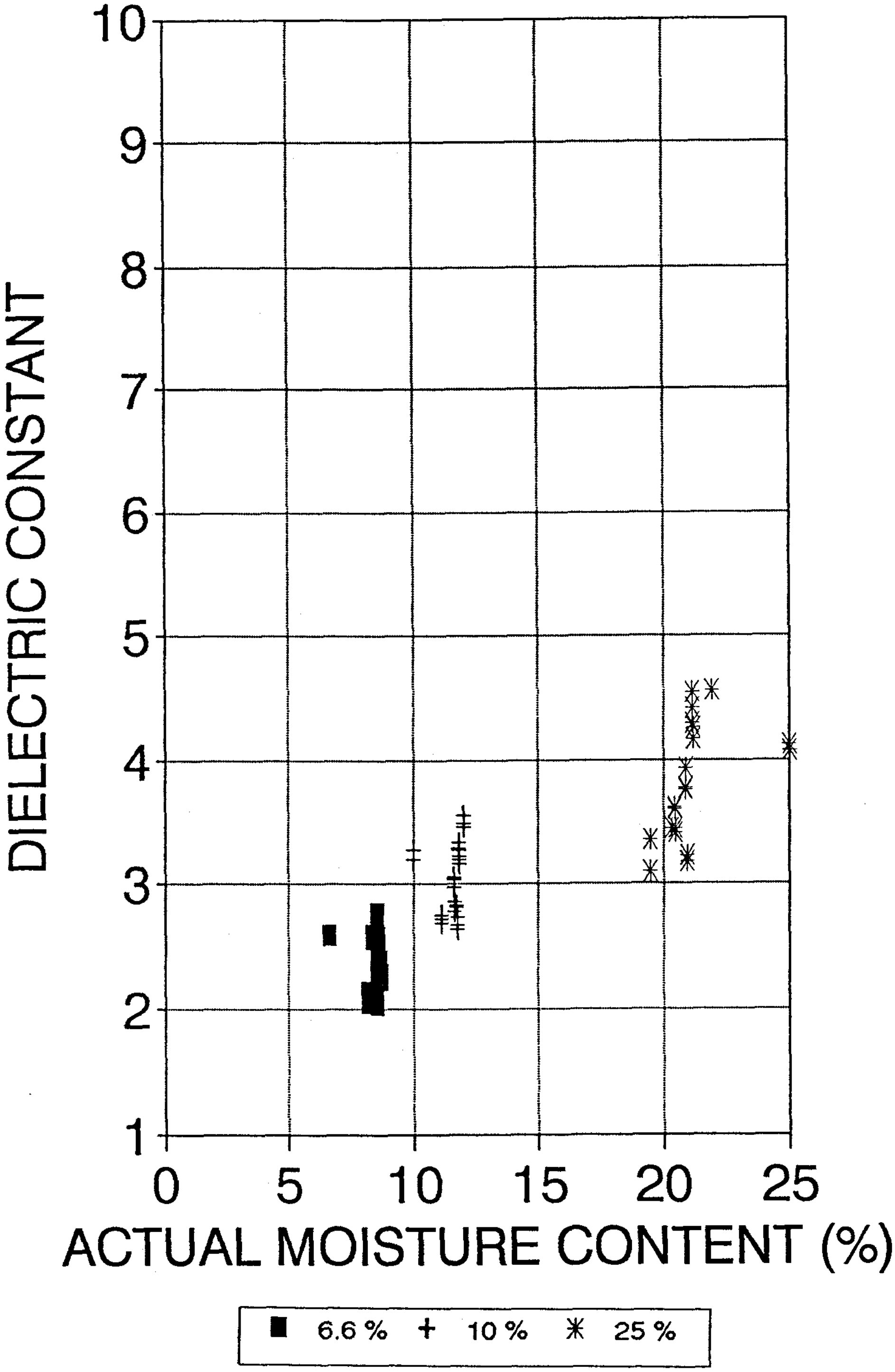

Figure A.4.31. The effect of moisture on the dielectric constant of light blue stain at 10 MHz.

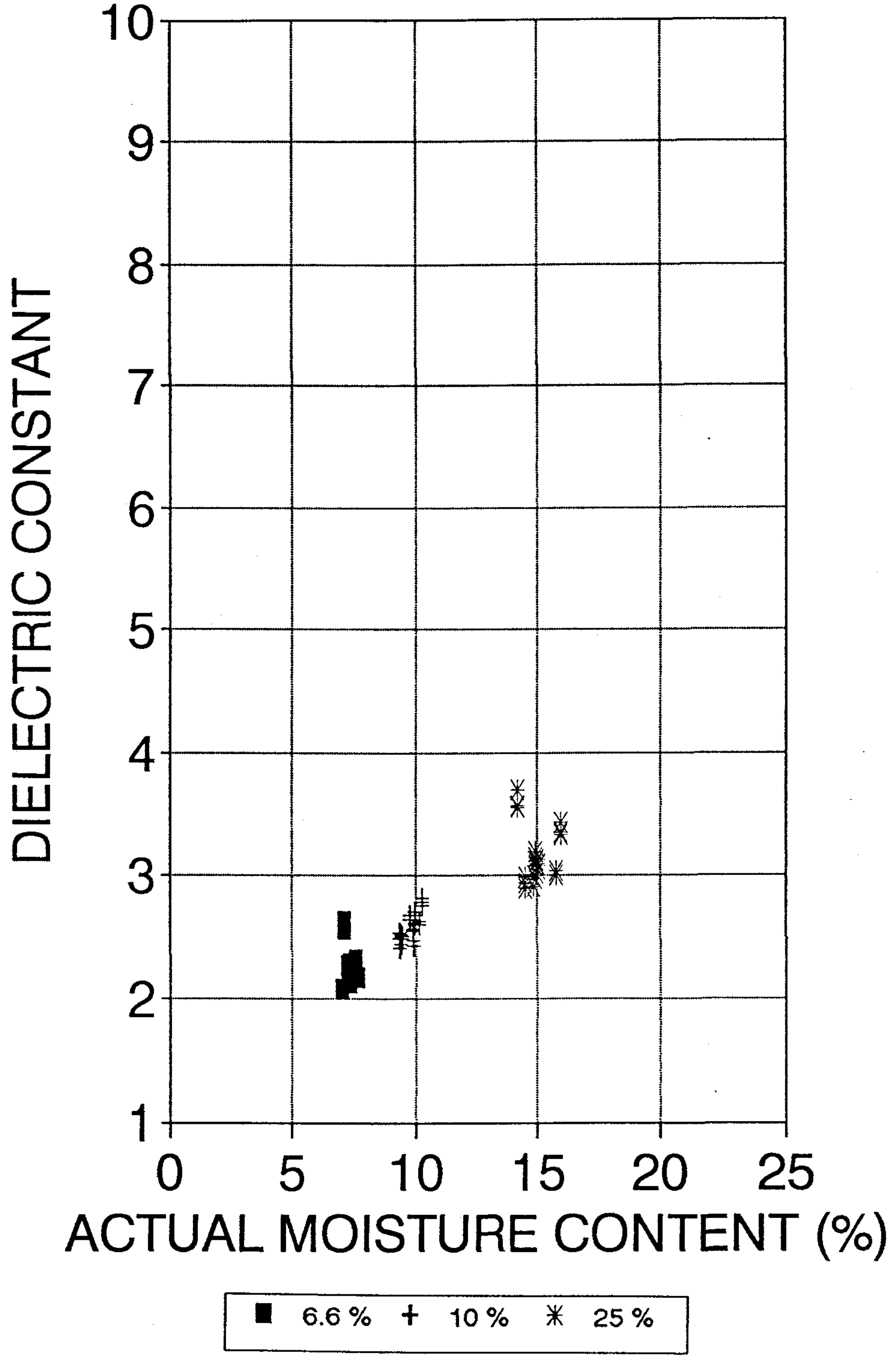

Figure A.4.32. The effect of moisture on the dielectric constant of clearwood at 10 MHz.

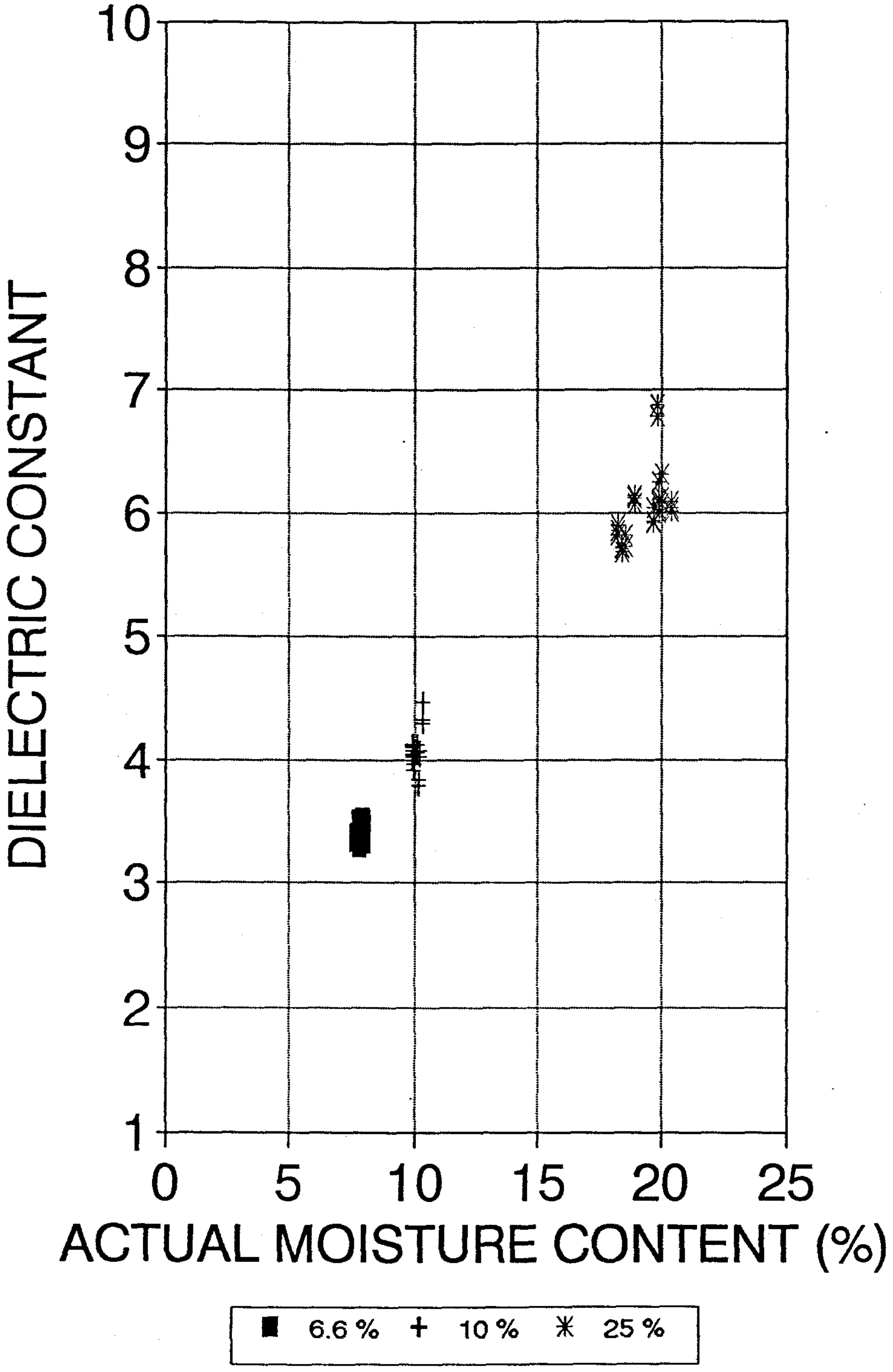

Figure A.4.33. The effect of moisture on the dielectric constant of large loose knots at 20 MHz.

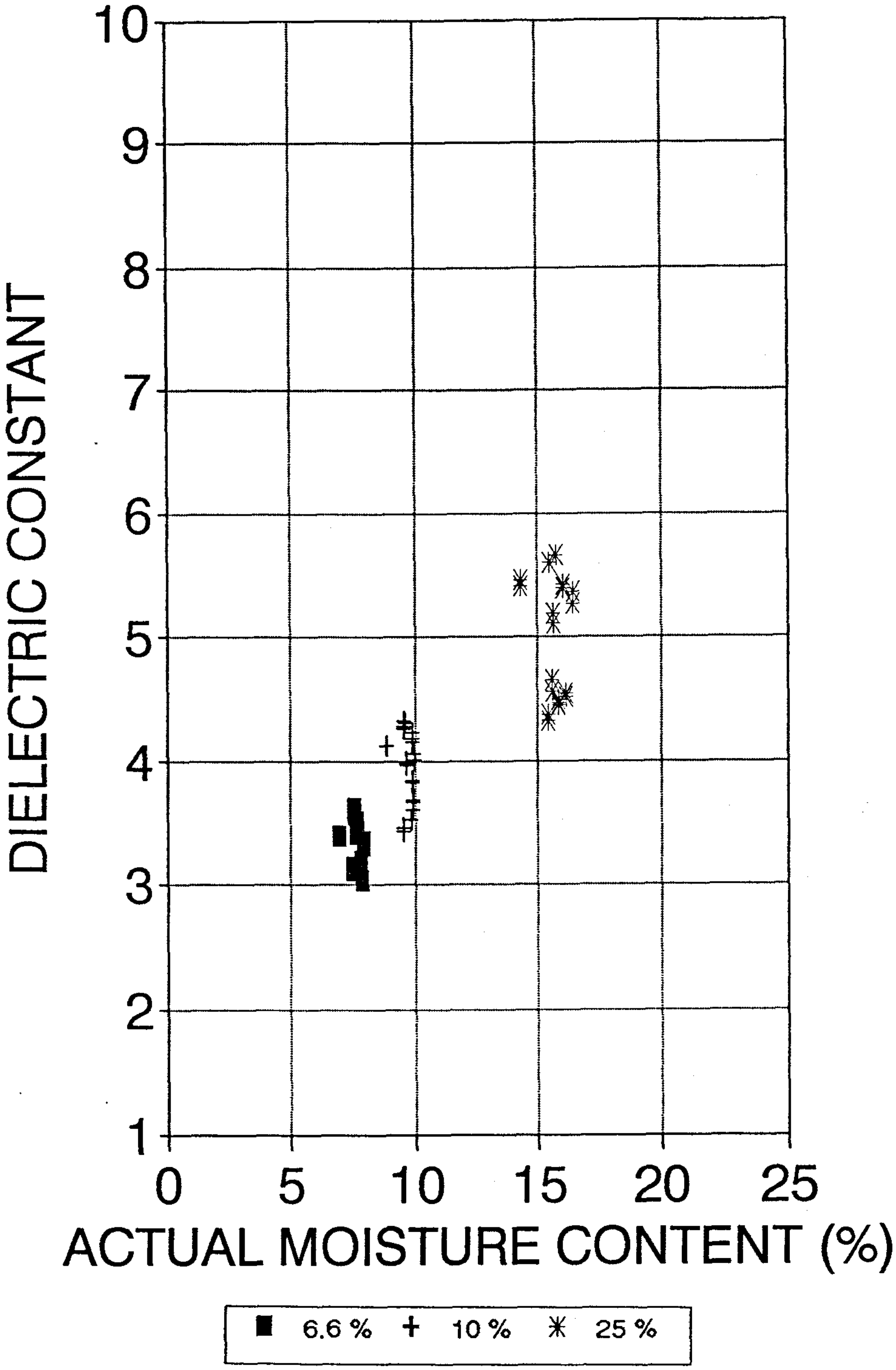

Figure A.4.34. The effect of moisture on the dielectric constant of medium loose knots at 20 MHz.

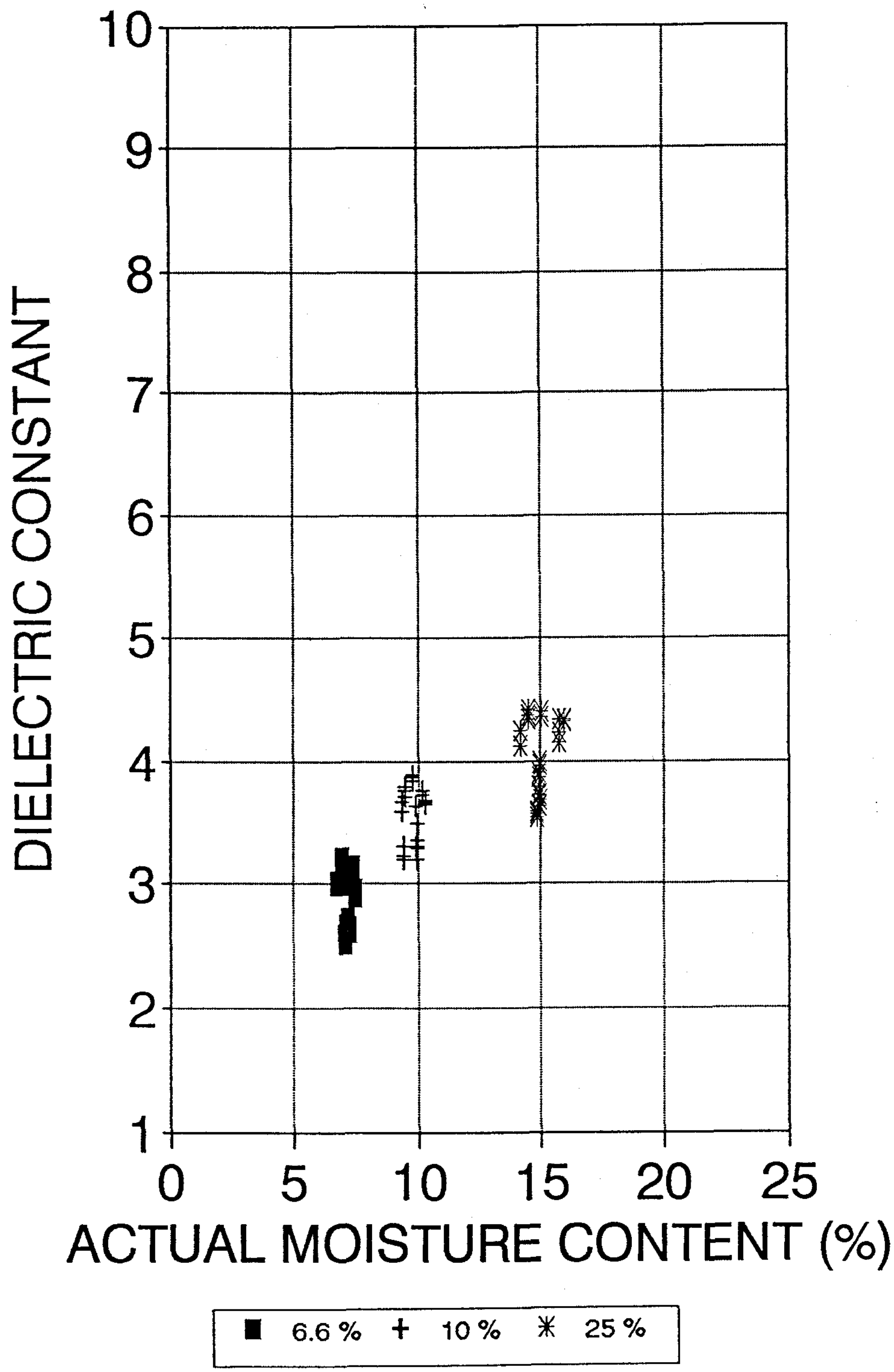

Figure A.4.35. The effect of moisture on the dielectric constant of small loose knots at 20 MHz.

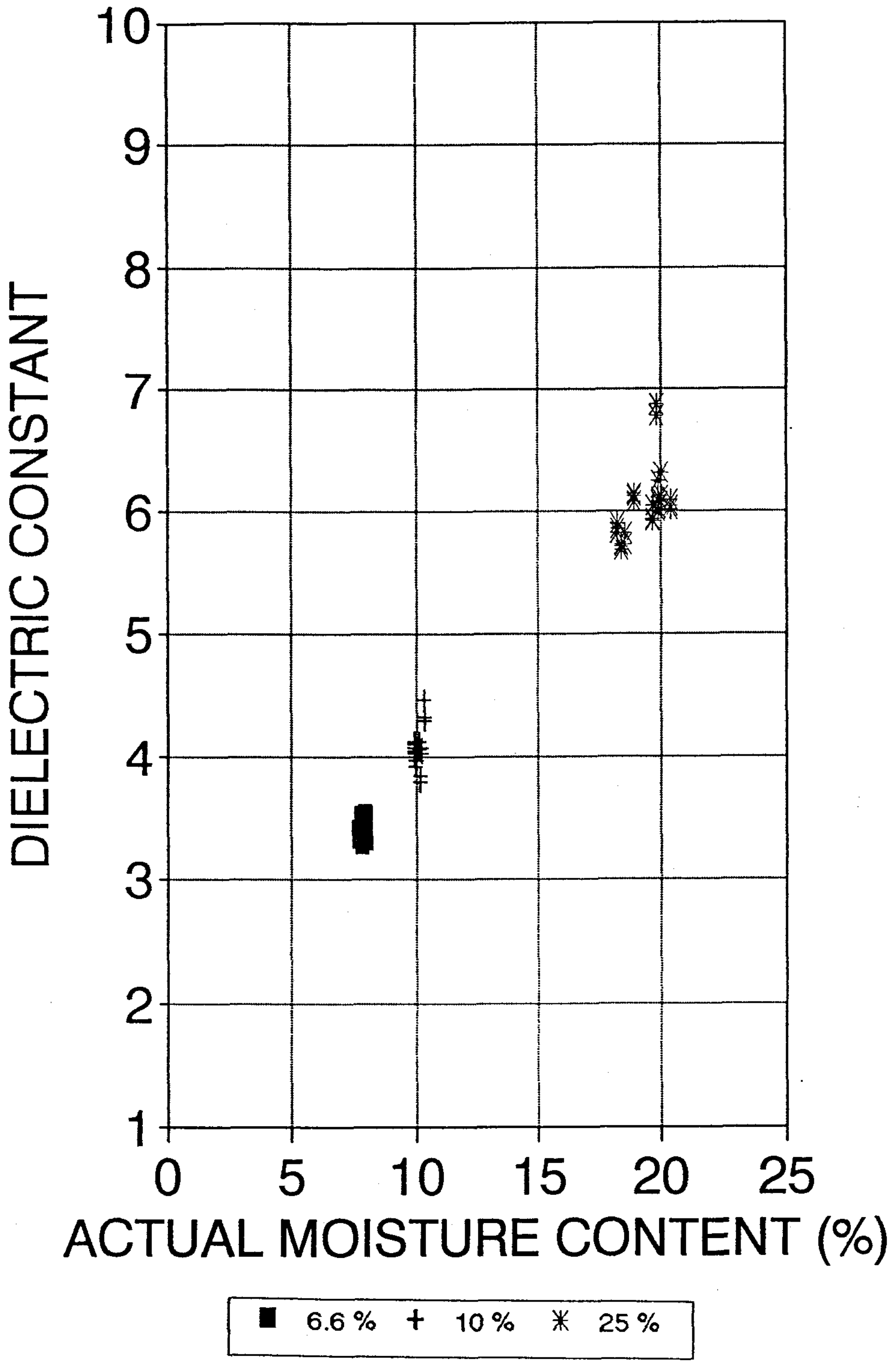

Figure A.4.36. The effect of moisture on the dielectric constant of large tight knots at 20 MHz.

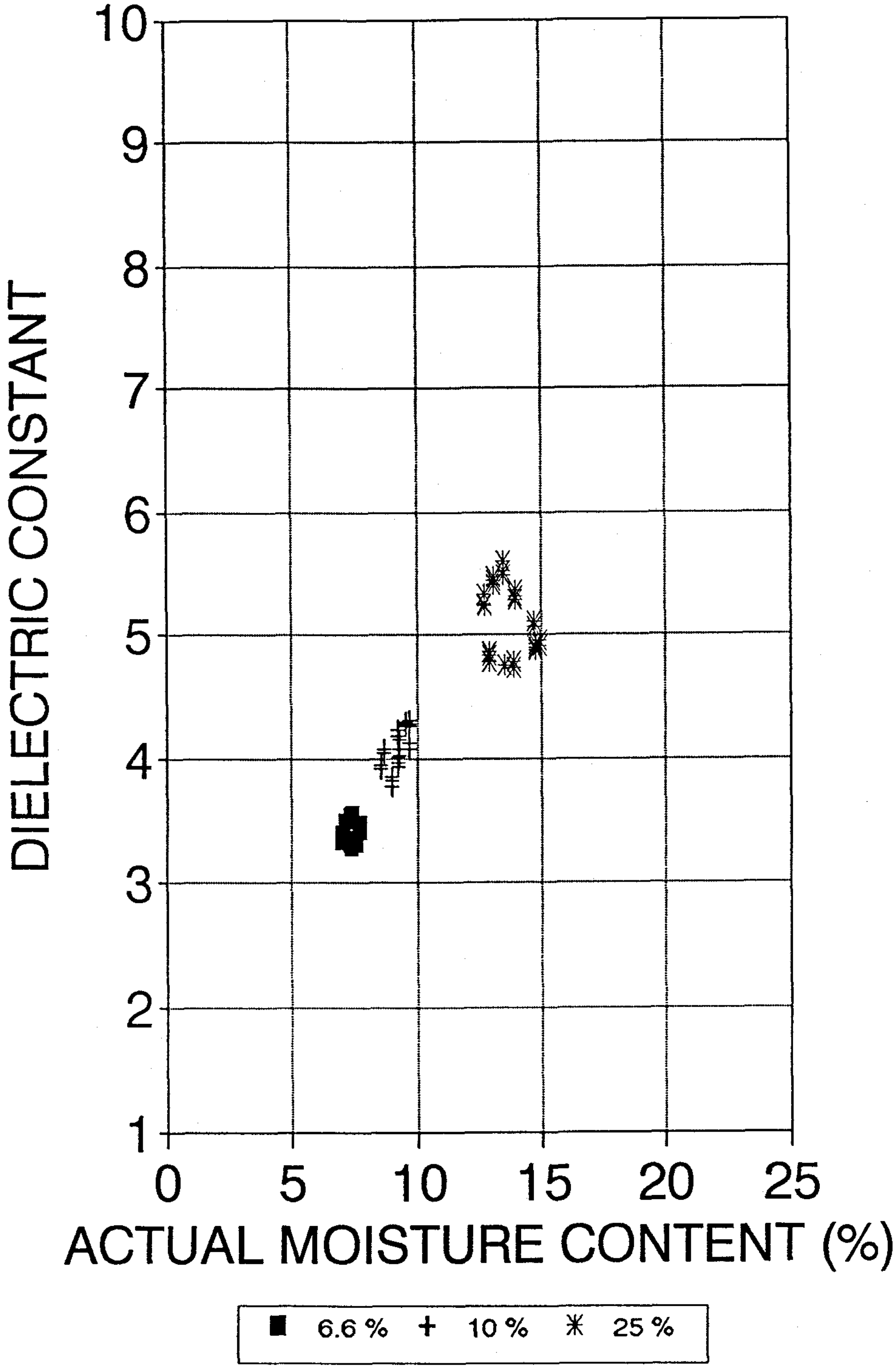

Figure A.4.37. The effect of moisture on the dielectric constant of medium tight knots at 20 MHz.

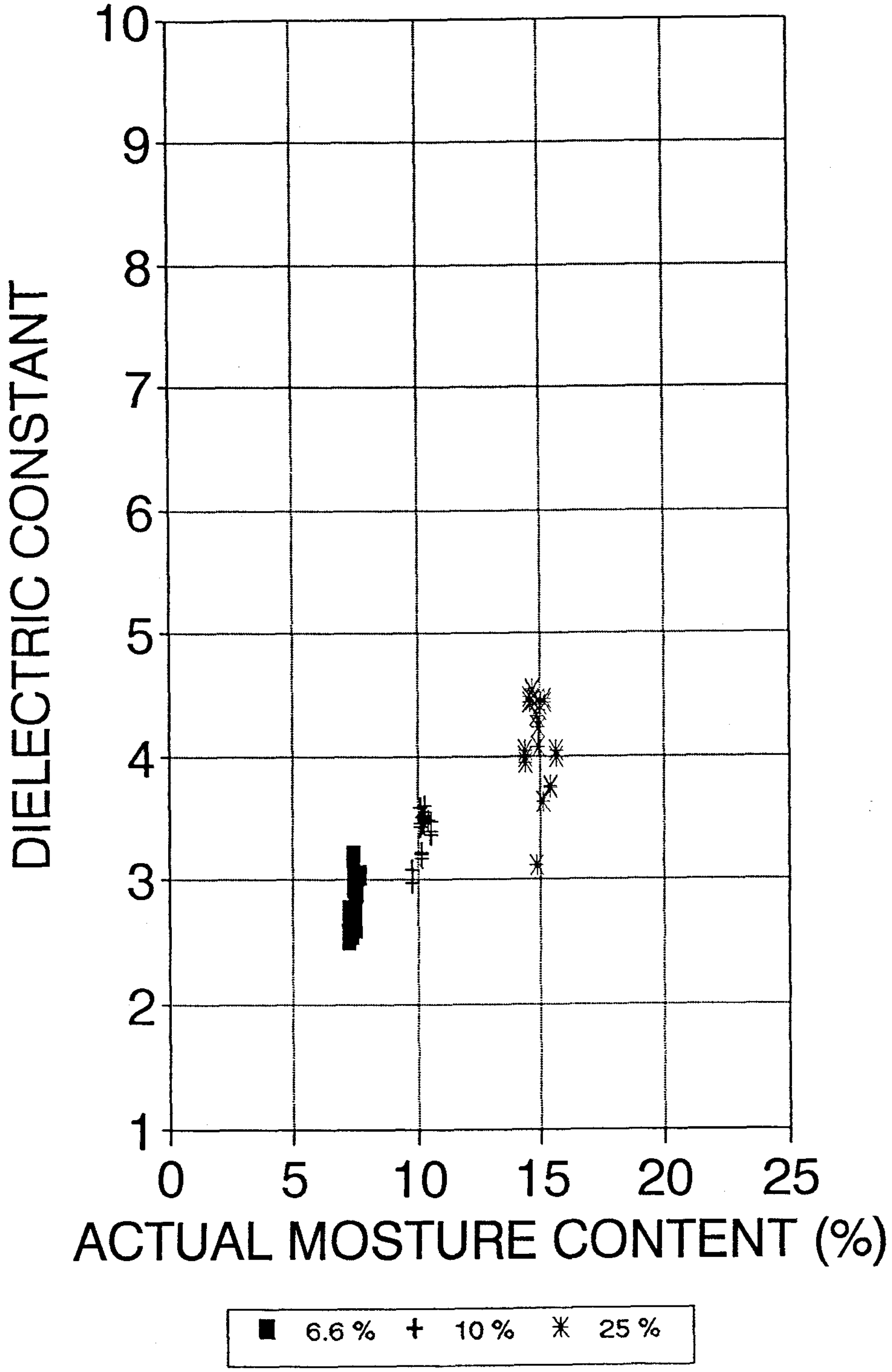

Figure A.4.38. The effect of moisture on the dielectric constant of small tight knots at 20 MHz.

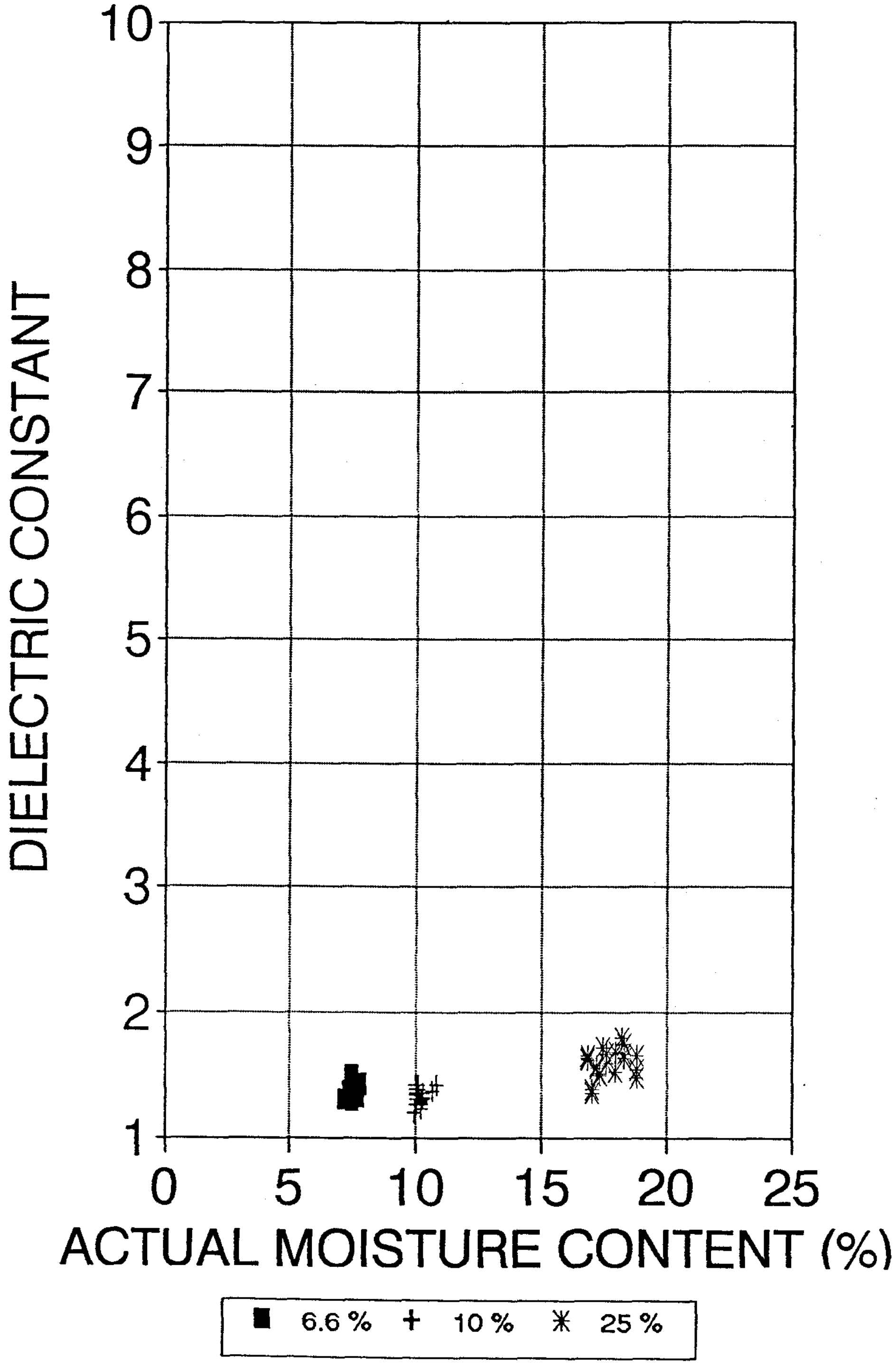

Figure A.4.39. The effect of moisture on the dielectric constant of large open holes at 20 MHz.

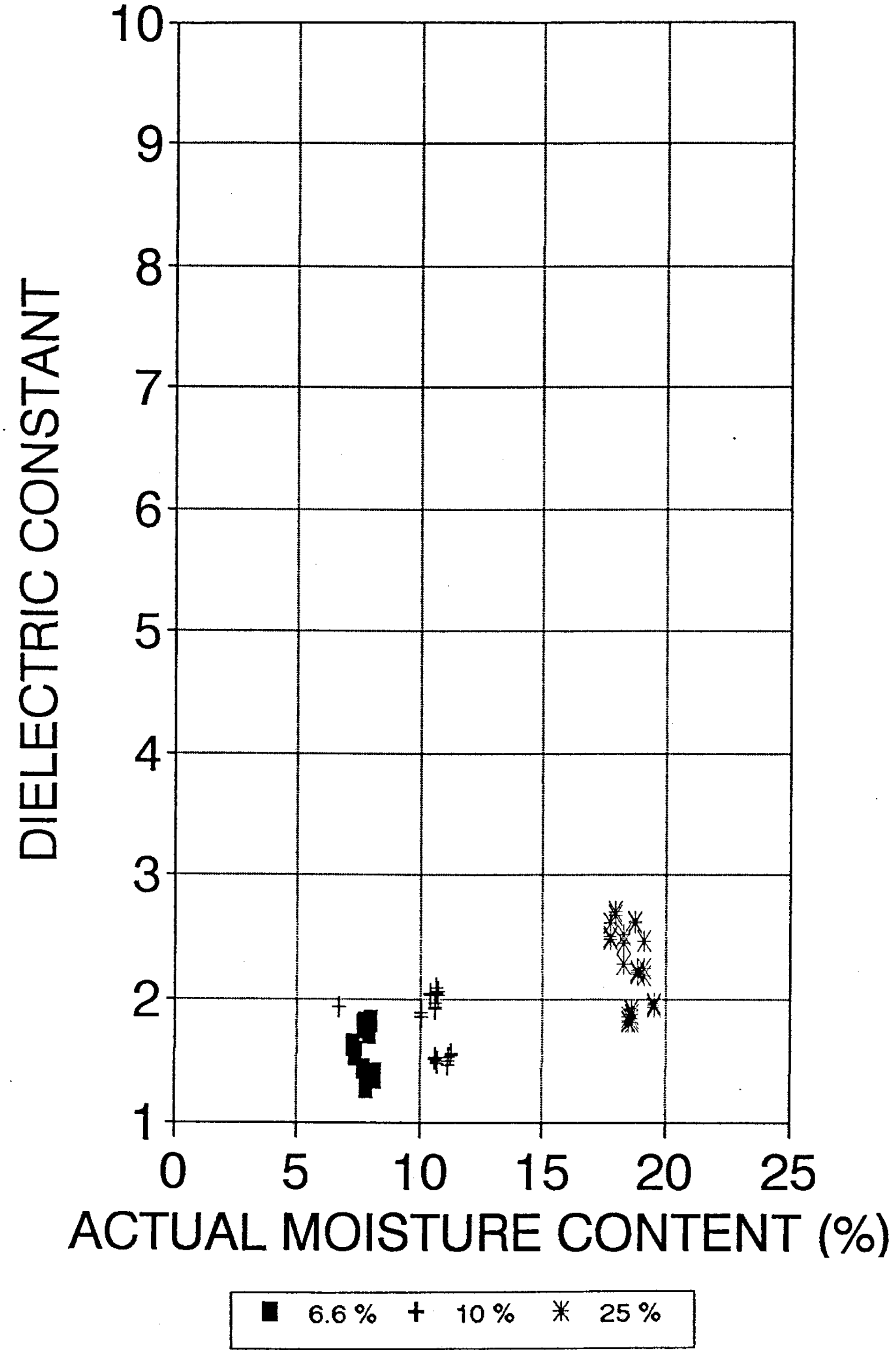

Figure A.4.40. The effect of moisture on the dielectric constant of medium open holes at 20 MHz.

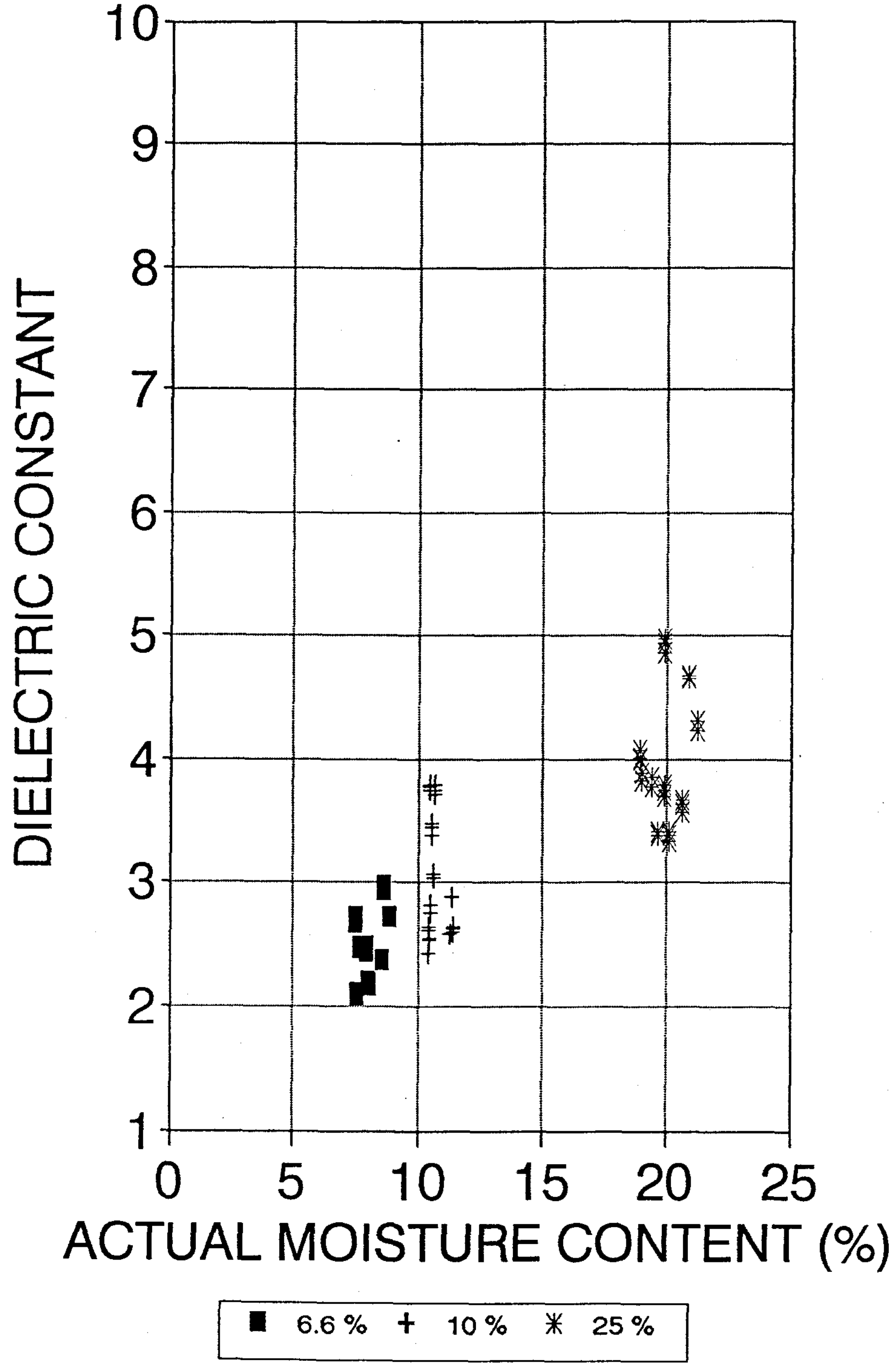

Figure A.4.41. The effect of moisture on the dielectric constant of small open holes at 20 MHz.

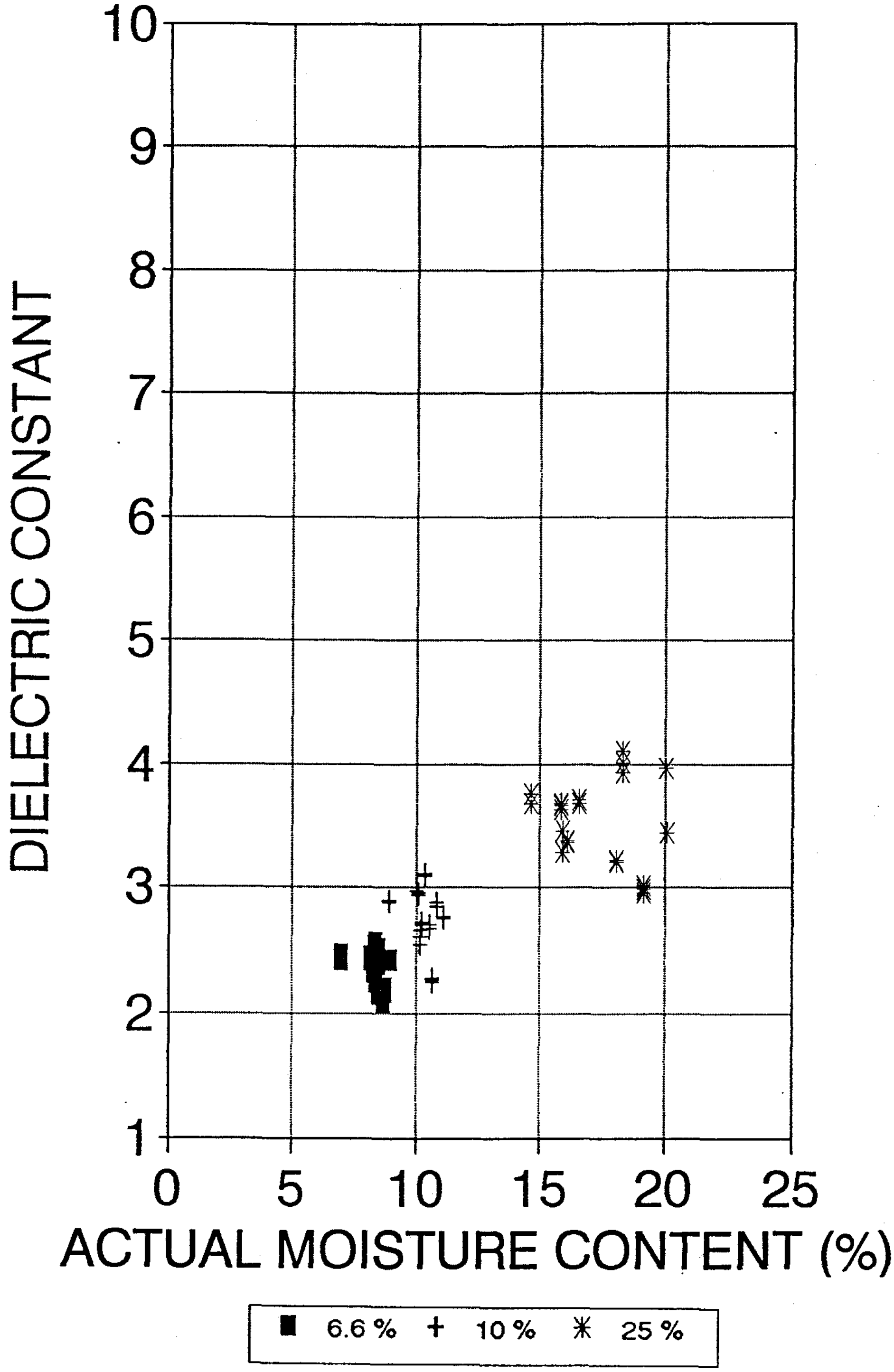

Figure A.4.42. The effect of moisture on the dielectric constant of large pitch pockets at 20 MHz.

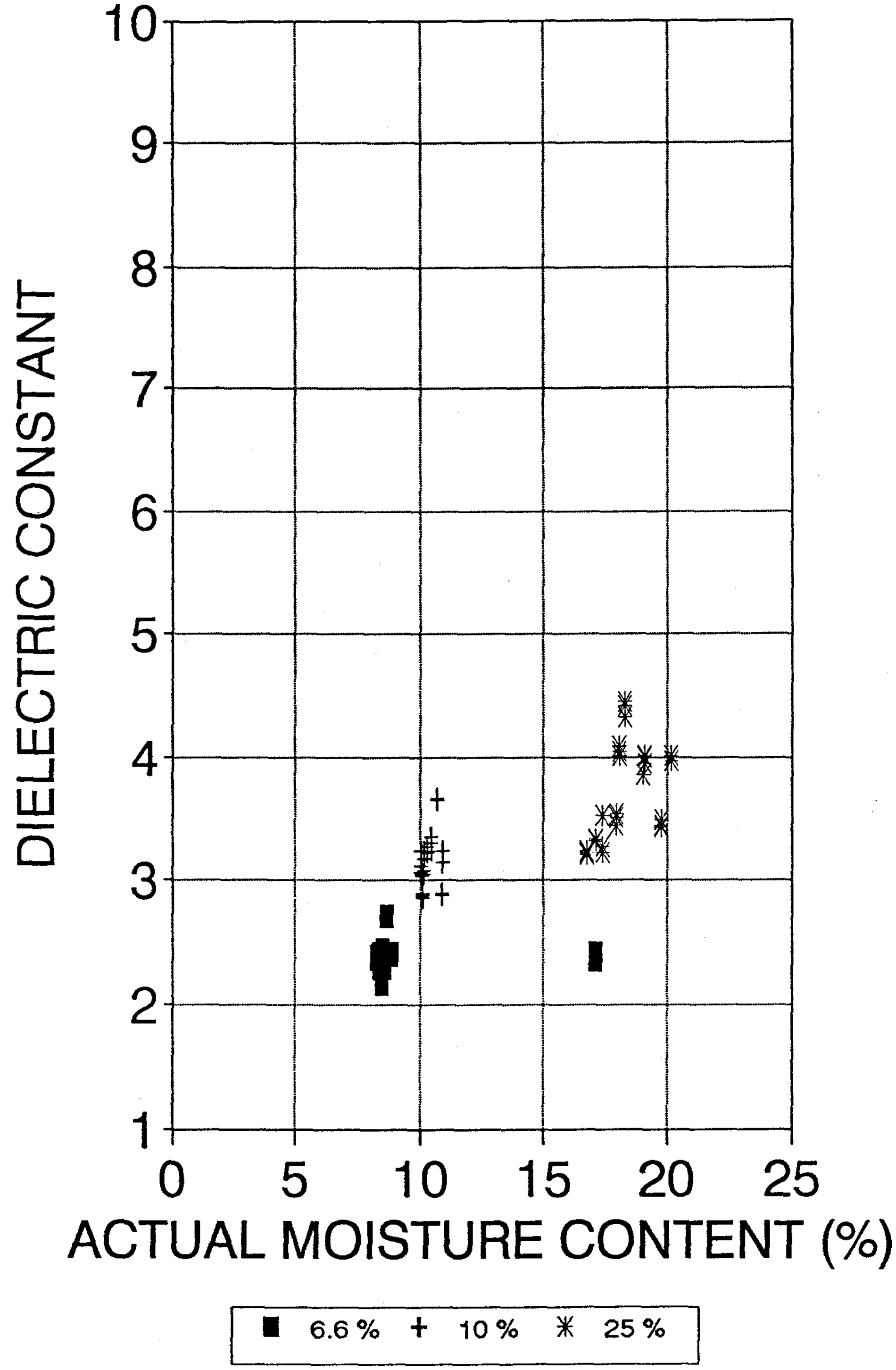

Figure A.4.43. The effect of moisture on the dielectric constant of small pitch pockets at 20 MHz.

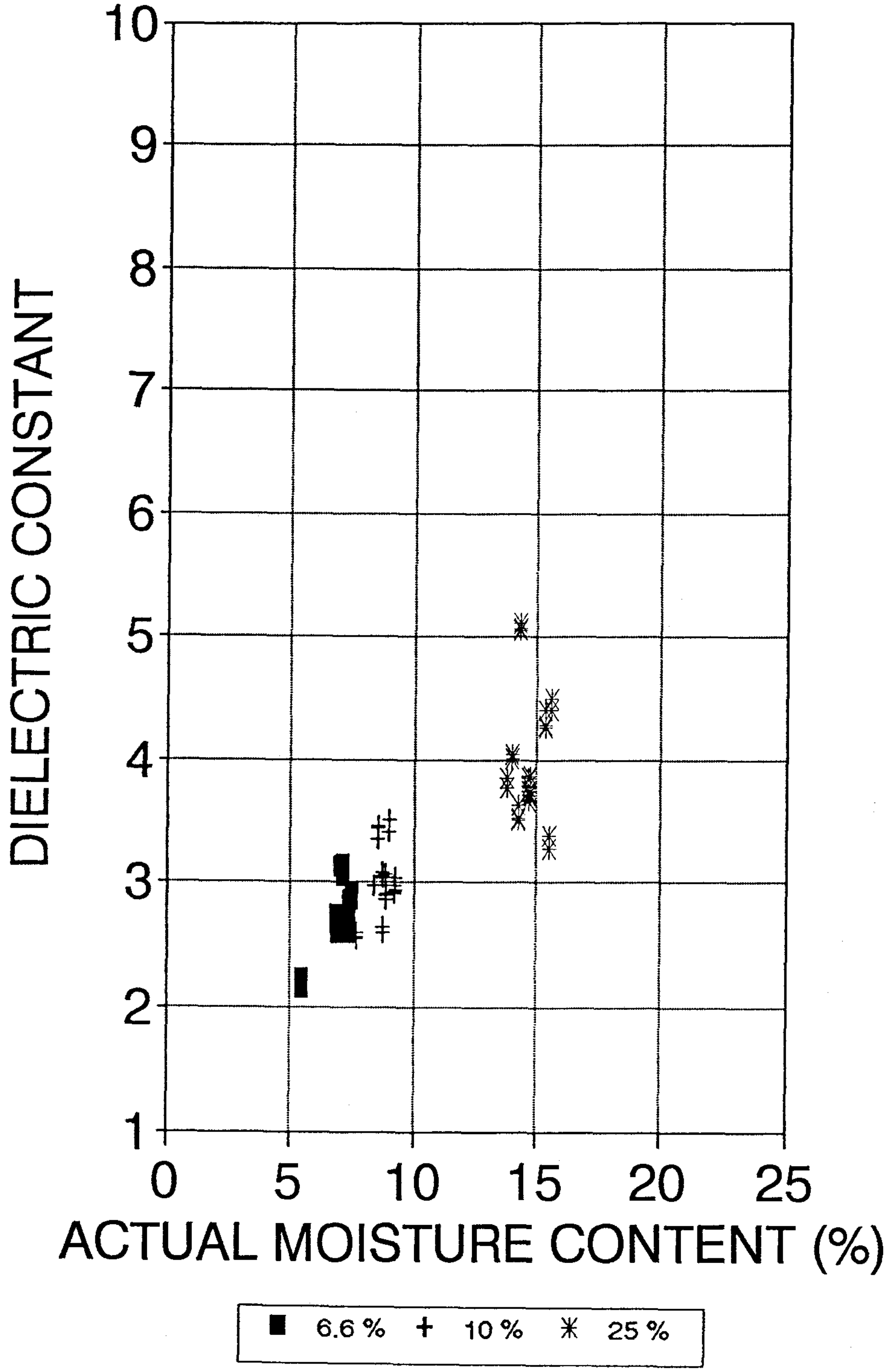

Figure A.4.44. The effect of moisture on the dielectric constant of heavy pitch streaks at 20 MHz.

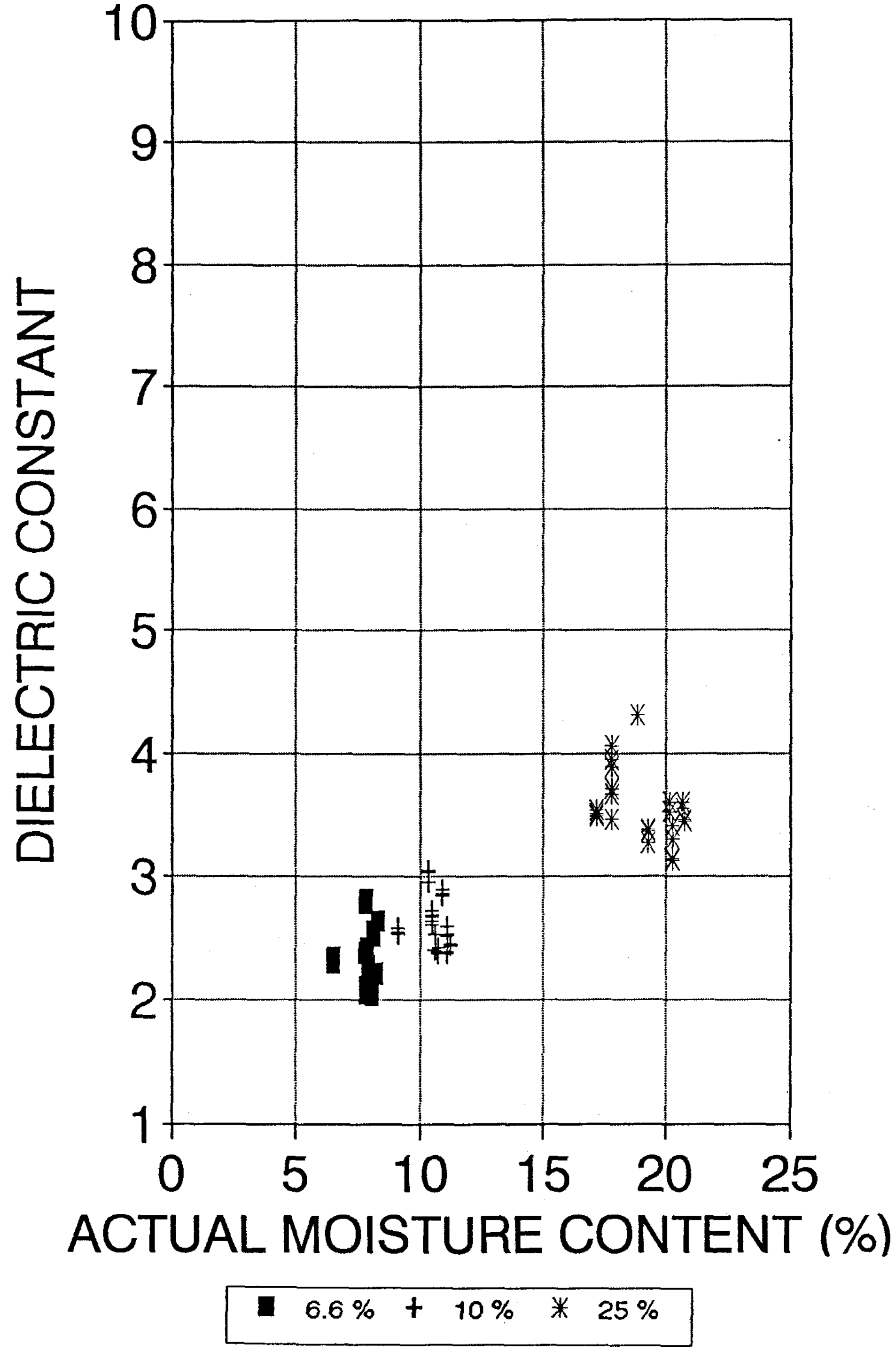

Figure A.4.45. The effect of moisture on the dielectric constant of light pitch streaks at 20 MHz.

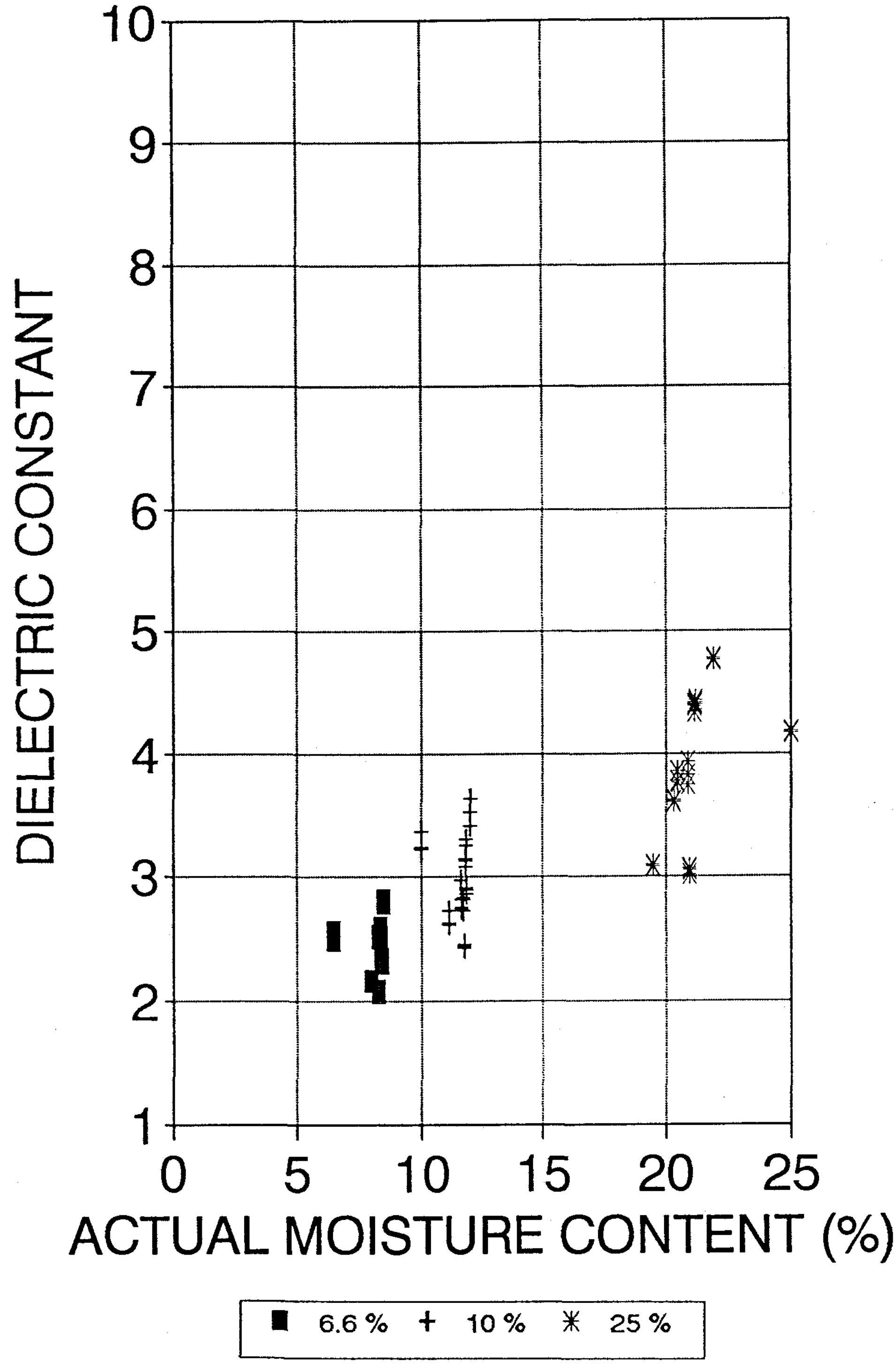

Figure A.4.46. The effect of moisture on the dielectric constant of heavy blue stain at 20 MHz.

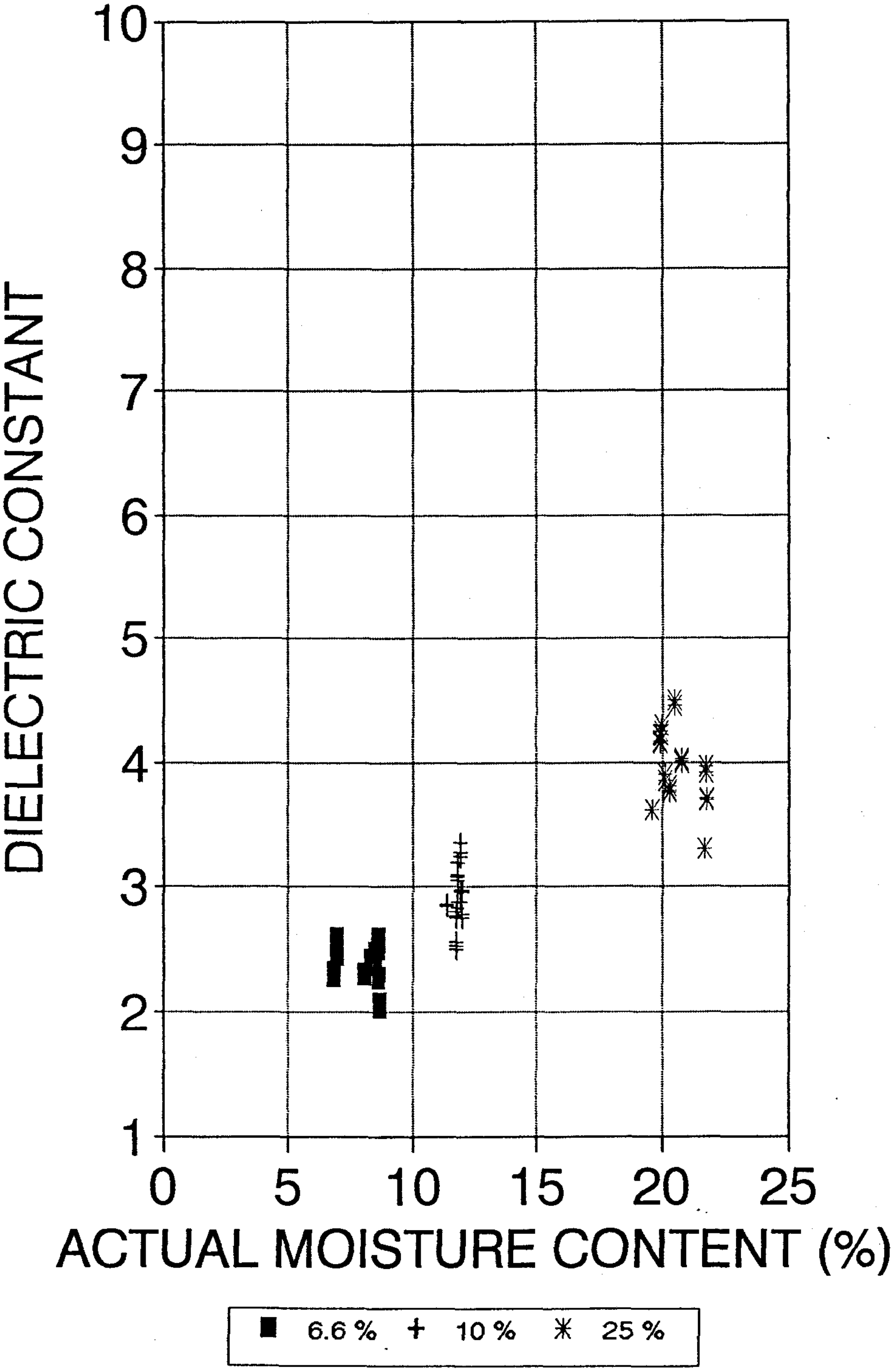

Figure A.4.47. The effect of moisture on the dielectric constant of light blue stain at 20 MHz.

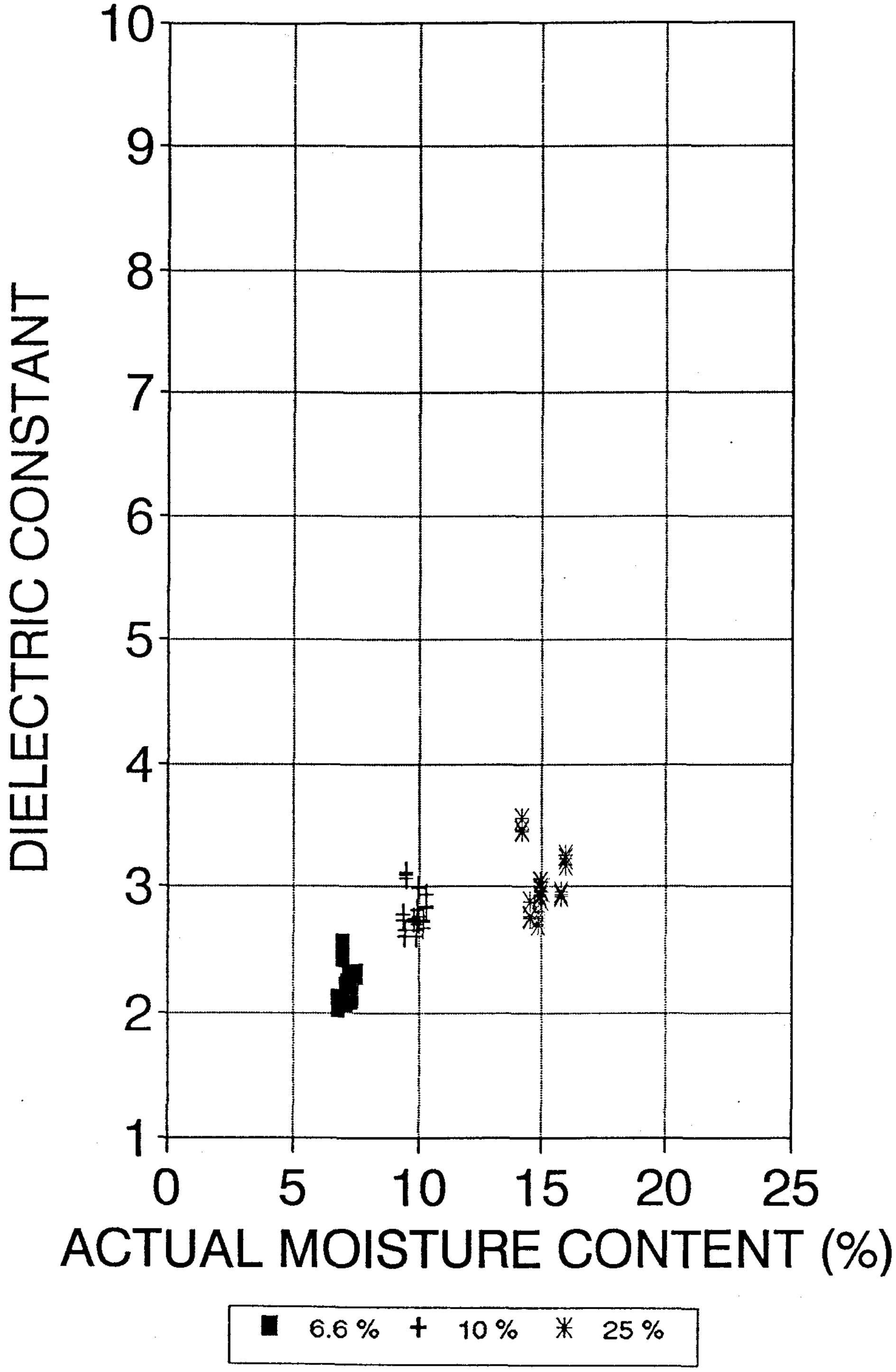

Figure A.4.48. The effect of moisture on the dielectric constant of clearwood at 20 MHz.

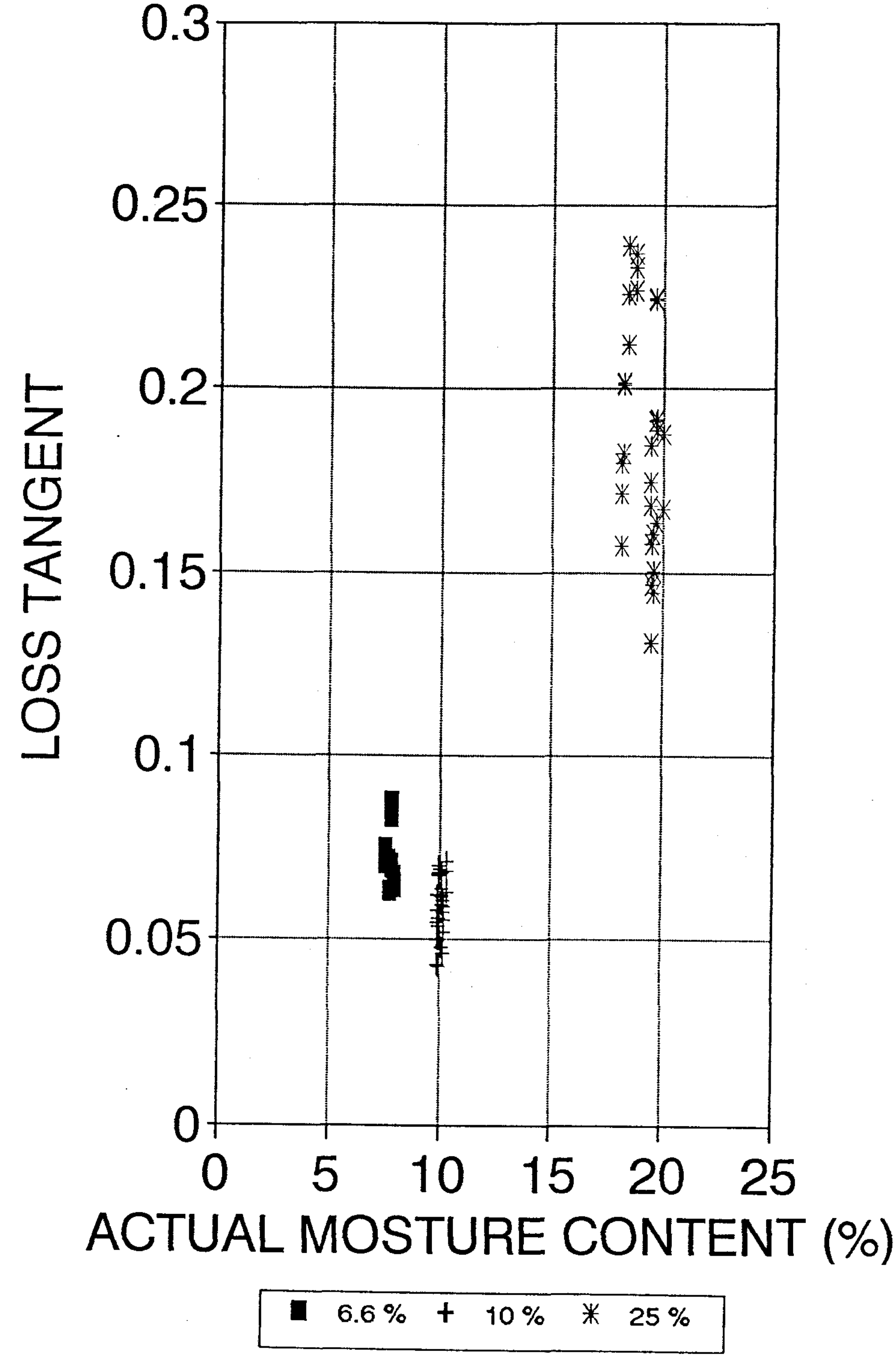

Figure A.4.49. The effect of moisture on the loss tangent of large loose knots at 1.4 MHz.

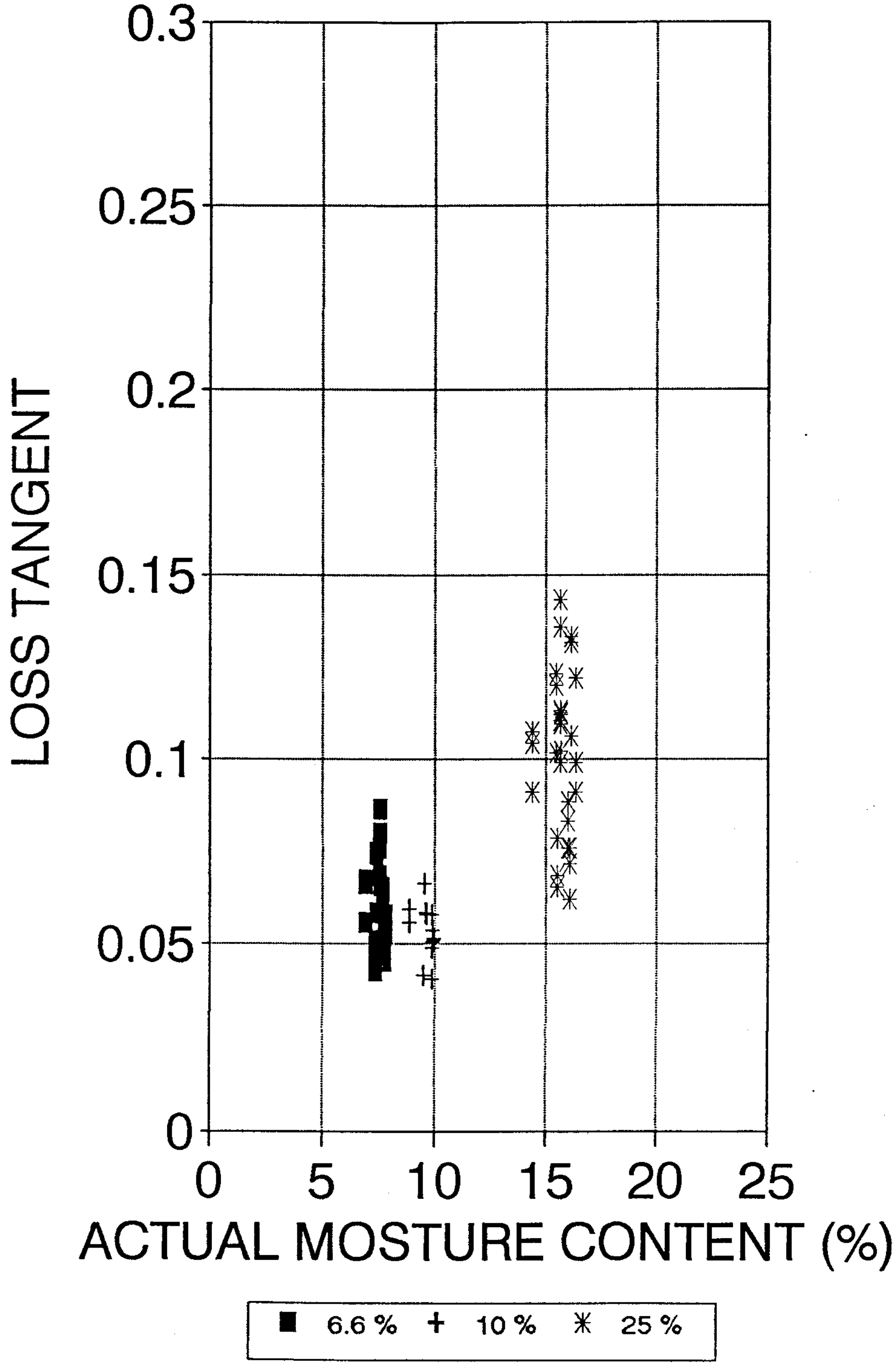

Figure A.4.50. The effect of moisture on the loss tangent of medium loose knots at 1.4 MHz.

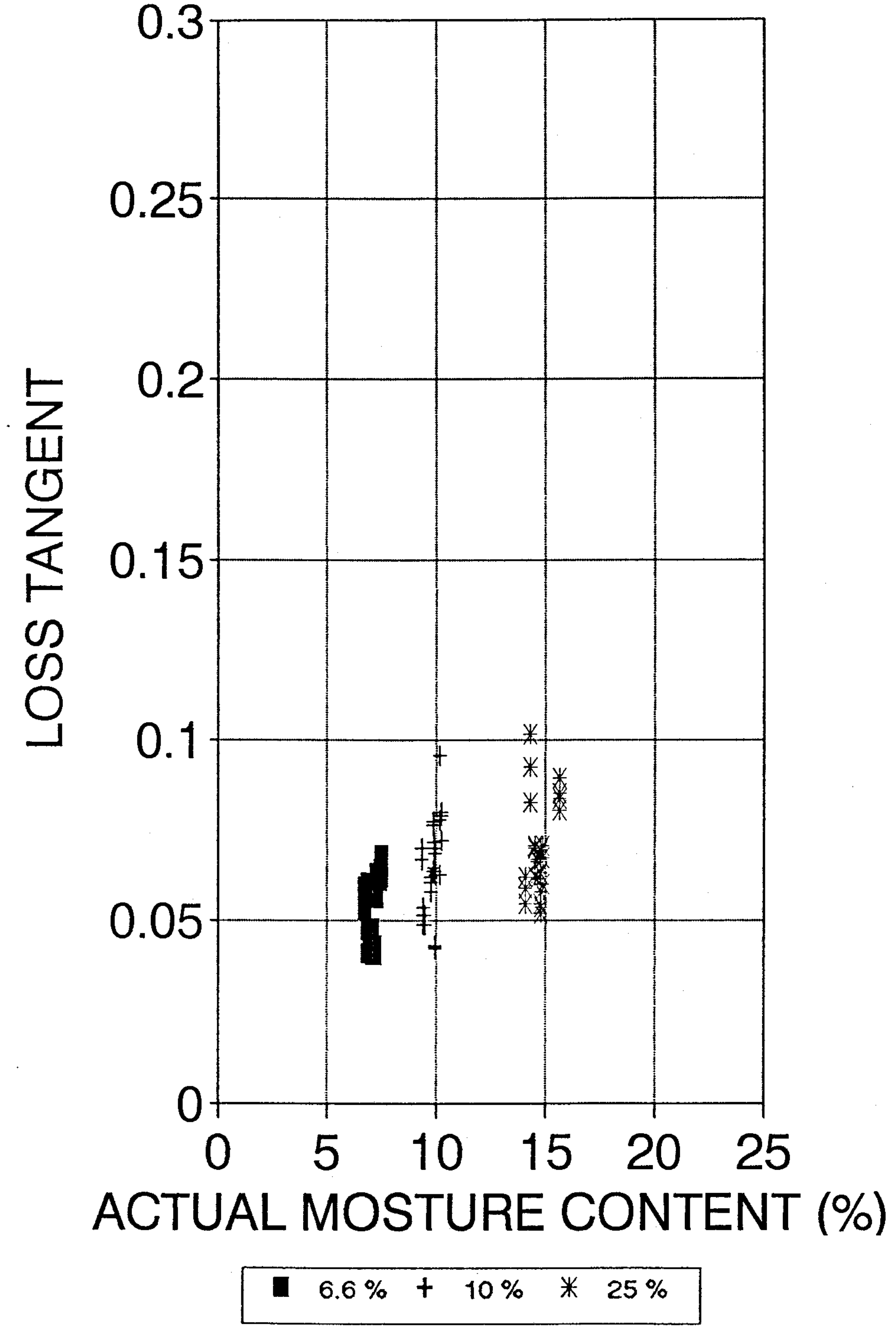

Figure A.4.51. The effect of moisture on the loss tangent of small loose knots at 1.4 MHz.

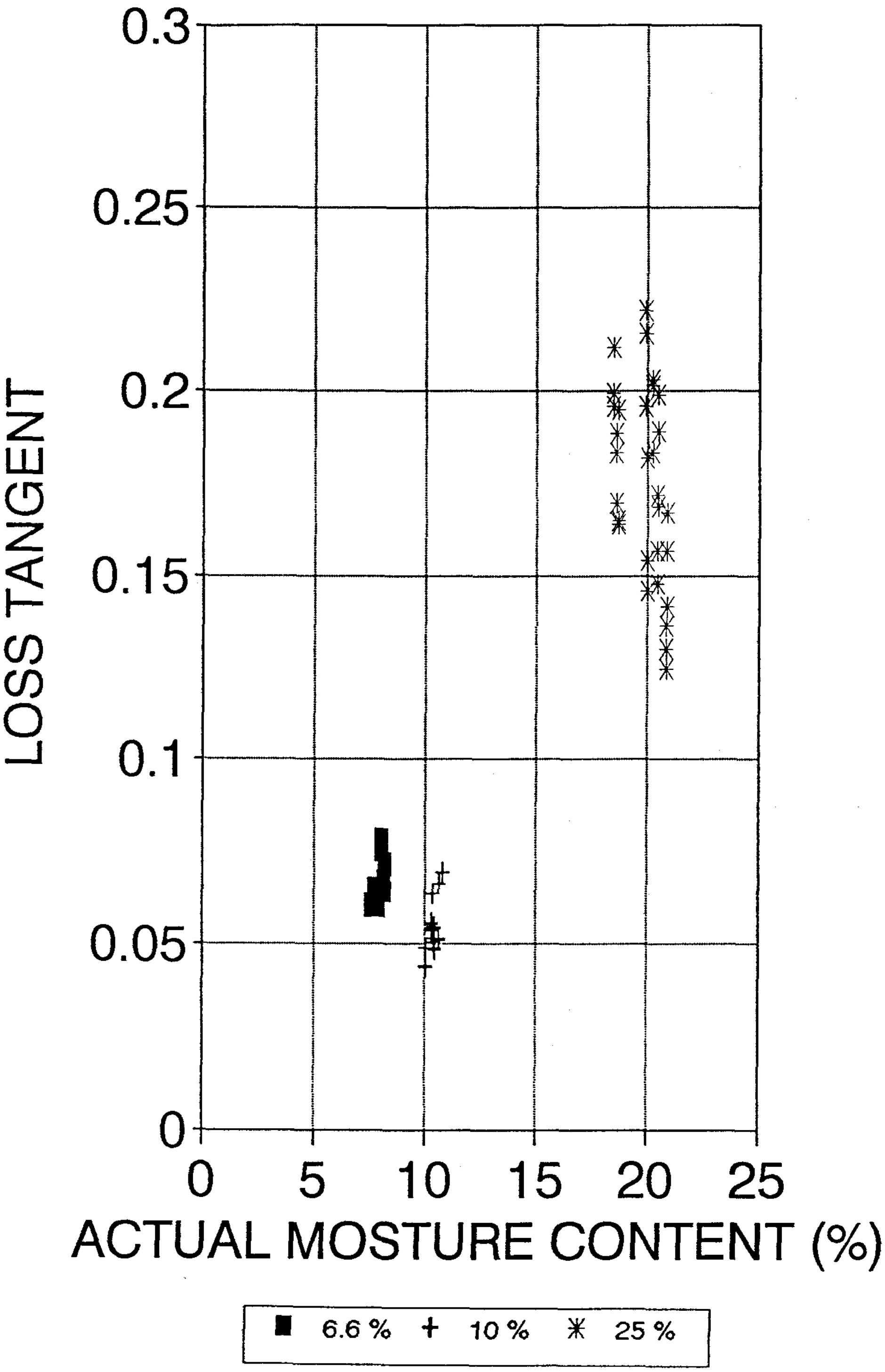

Figure A.4.52. The effect of moisture on the loss tangent of large tight knots at 1.4 MHz.

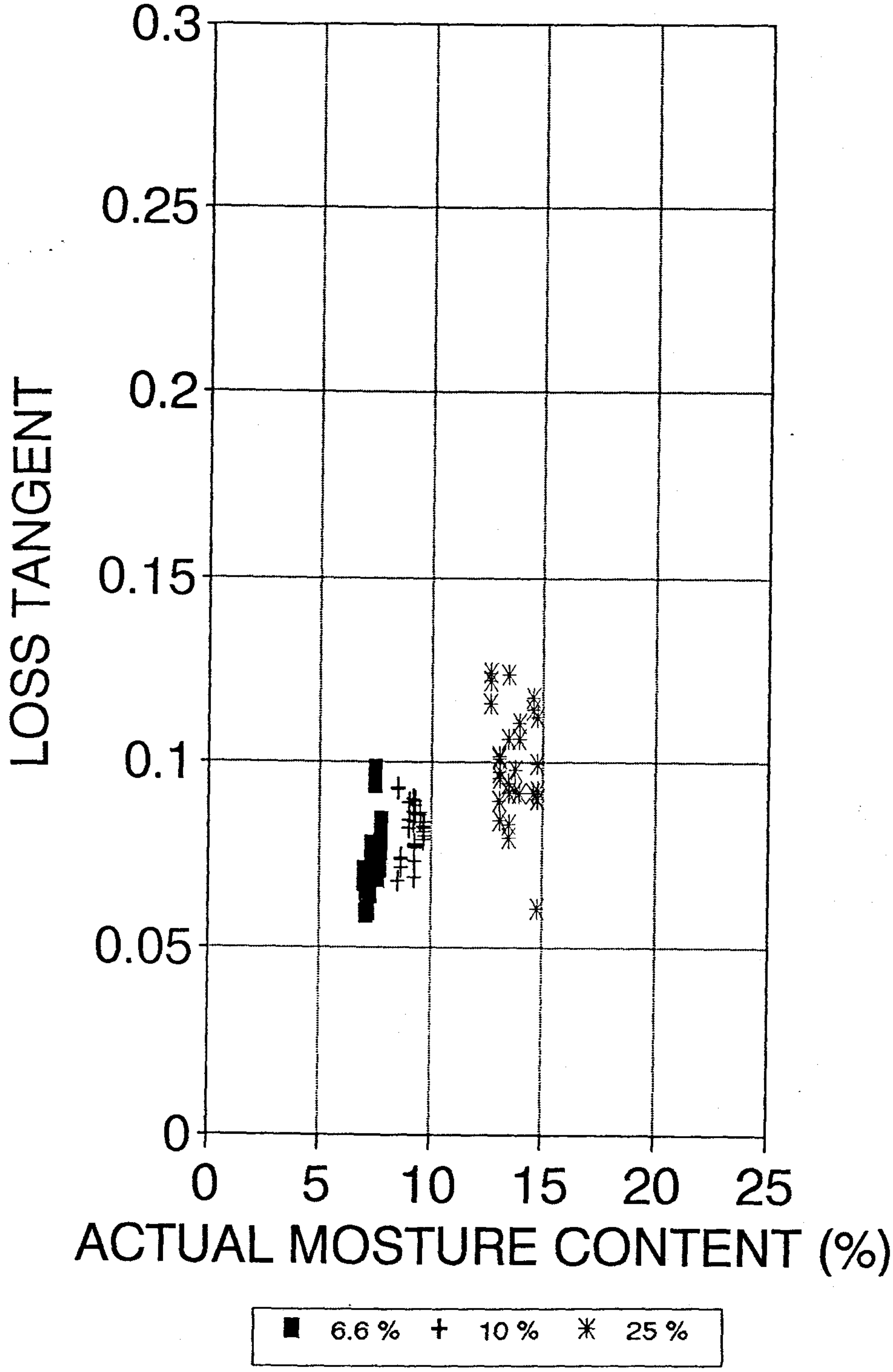

Figure A.4.53. The effect of moisture on the loss tangent of medium tight knots at 1.4 MHz.

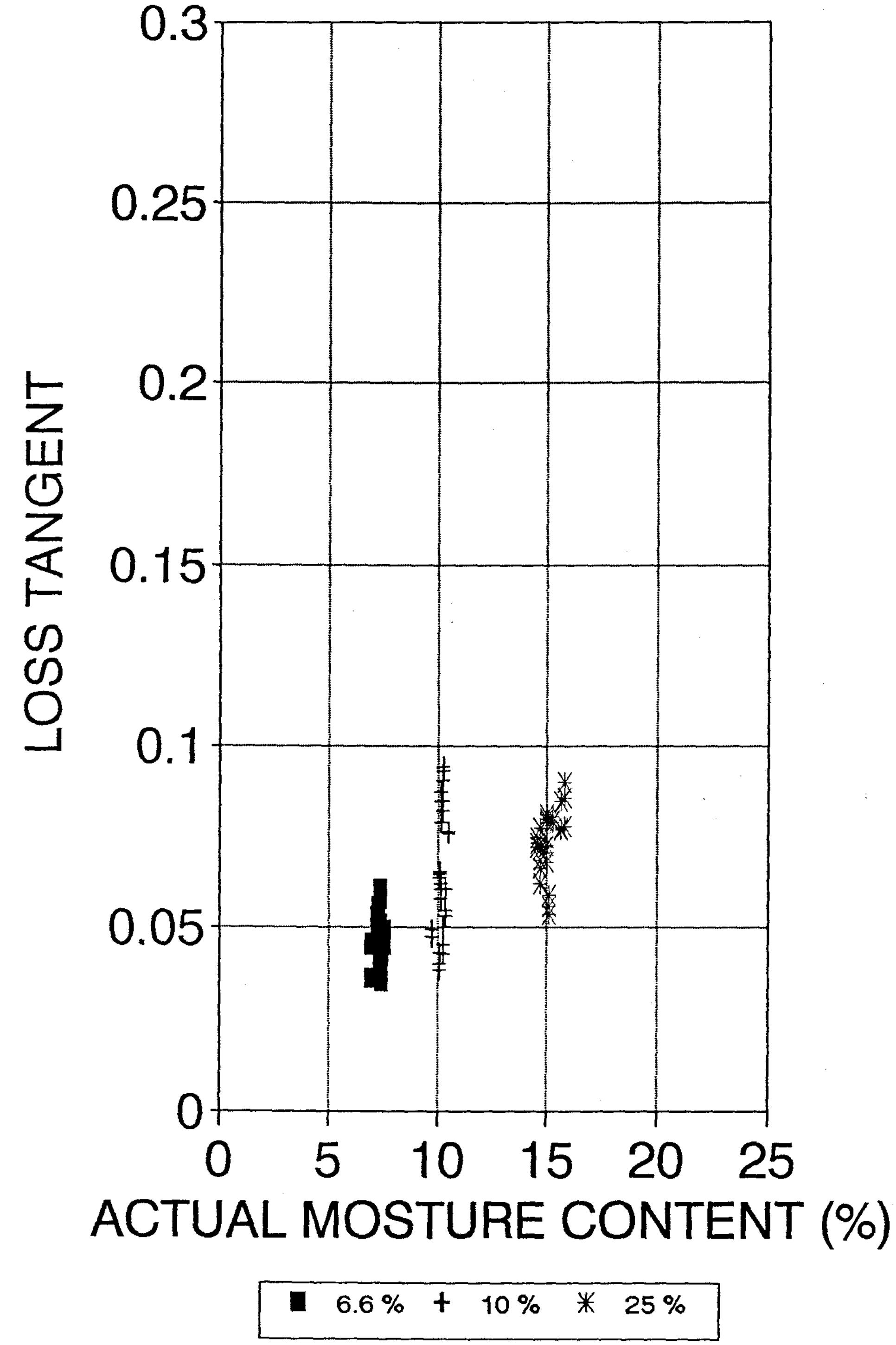

Figure A.4.54. The effect of moisture on the loss tangent of small tight knots at 1.4 MHz.

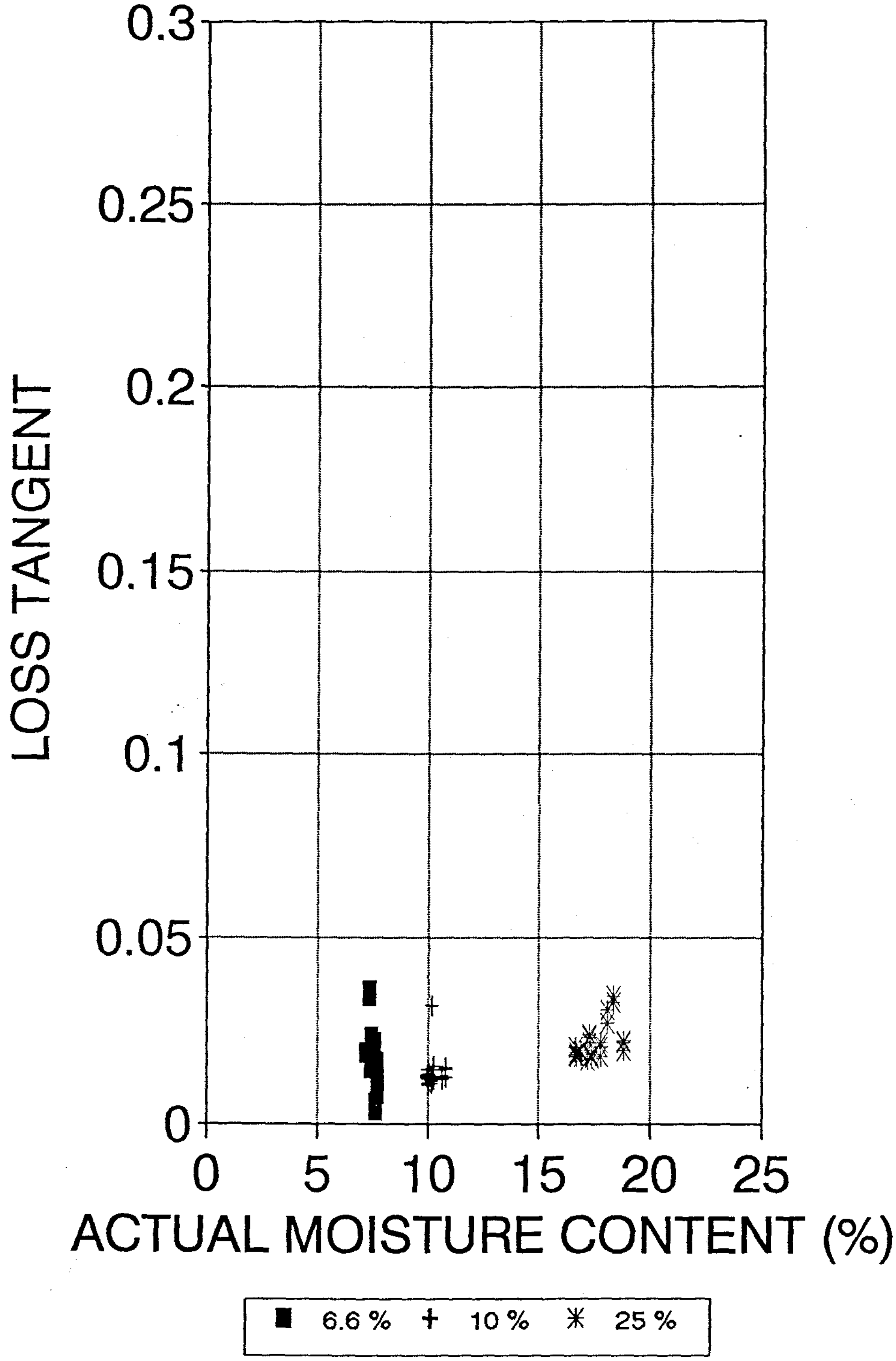

Figure A.4.55. The effect of moisture on the loss tangent of large open holes at 1.4 MHz.

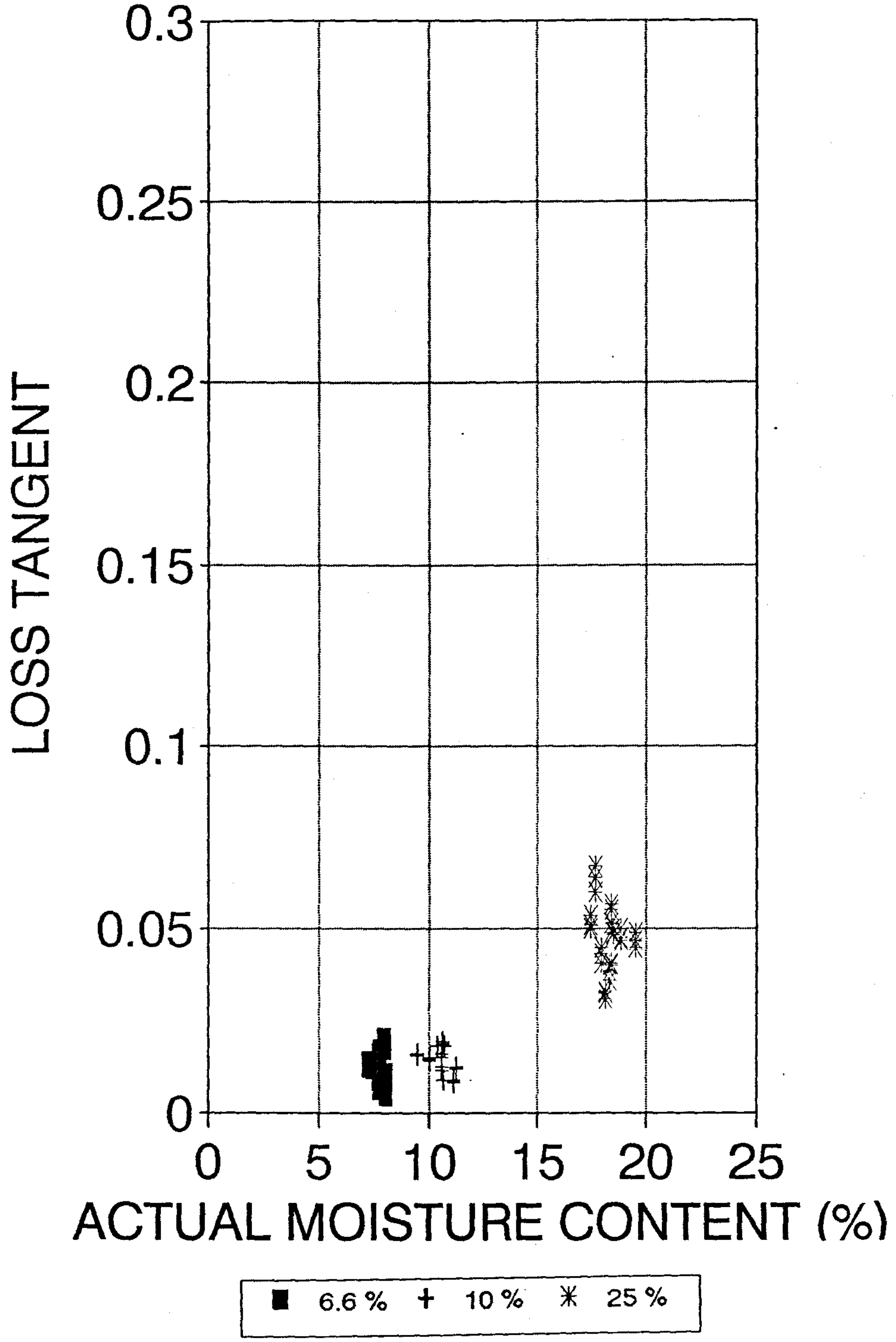

Figure A.4.56. The effect of moisture on the loss tangent of medium open holes at 1.4 MHz.

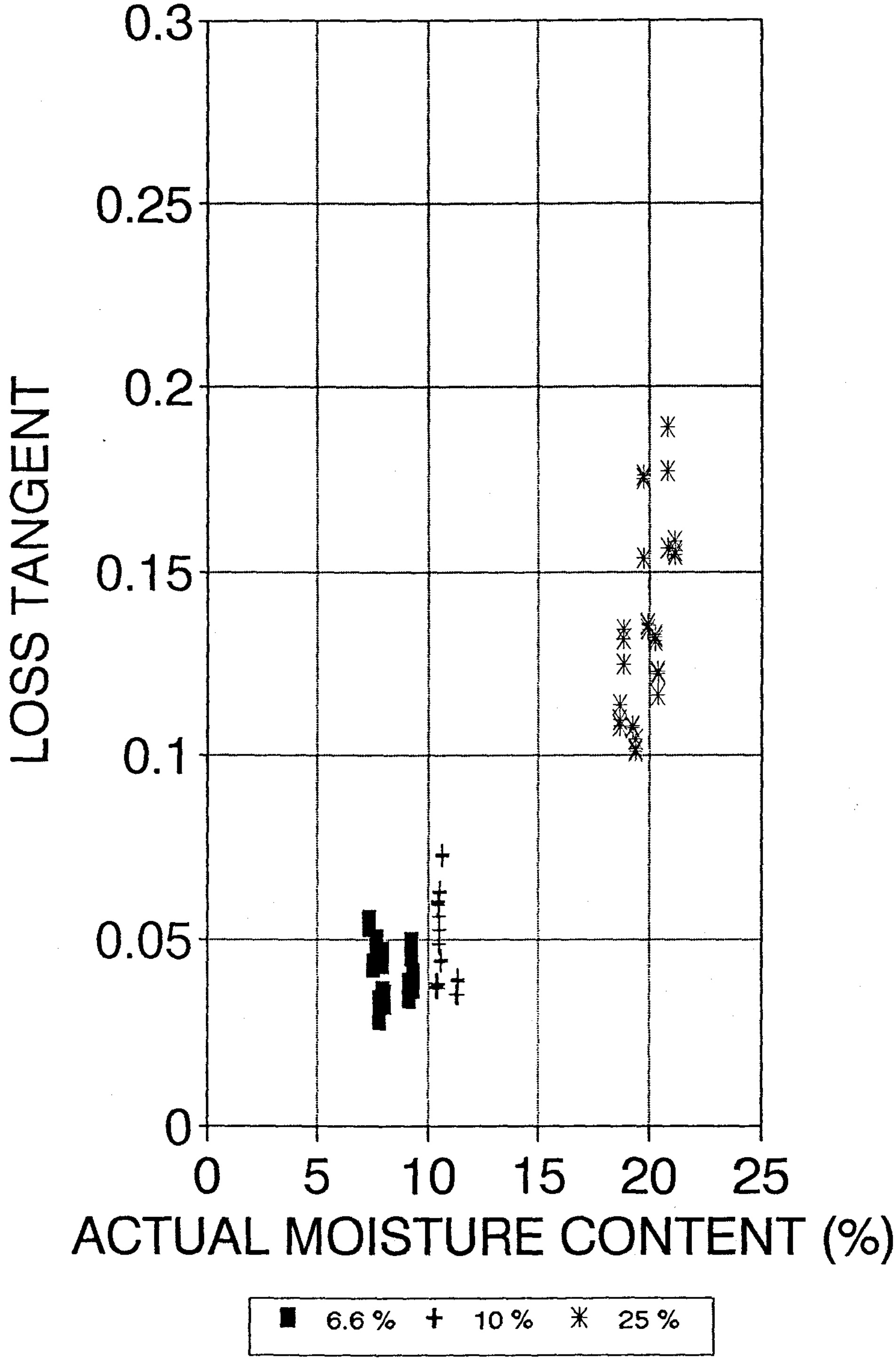

Figure A.4.57. The effect of moisture on the loss tangent of small open holes at 1.4 MHz.

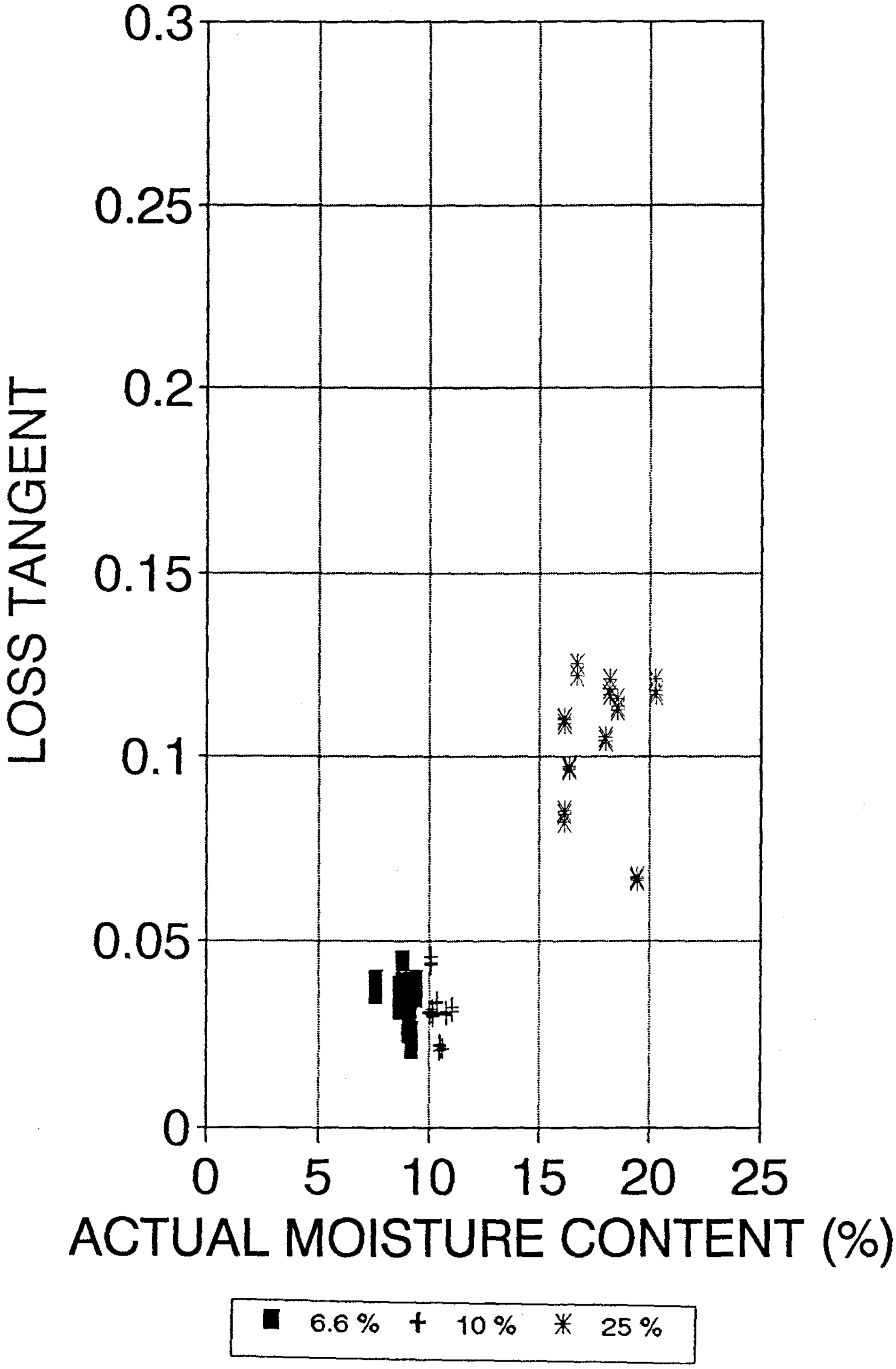

Figure A.4.58. The effect of moisture on the loss tangent of large pitch pockets at 1.4 MHz.

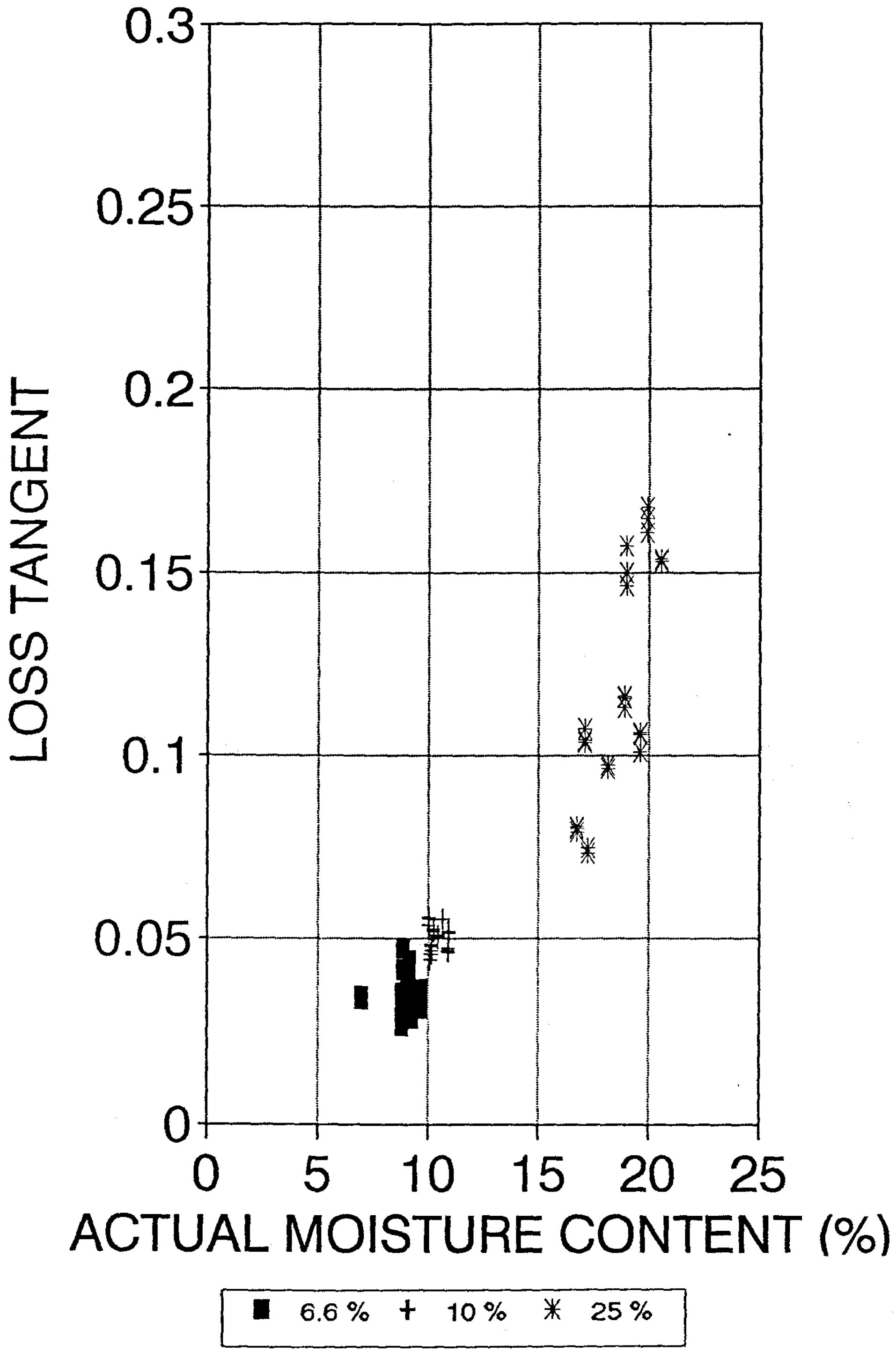

Figure A.4.59. The effect of moisture on the loss tangent of small pitch pockets at 1.4 MHz.

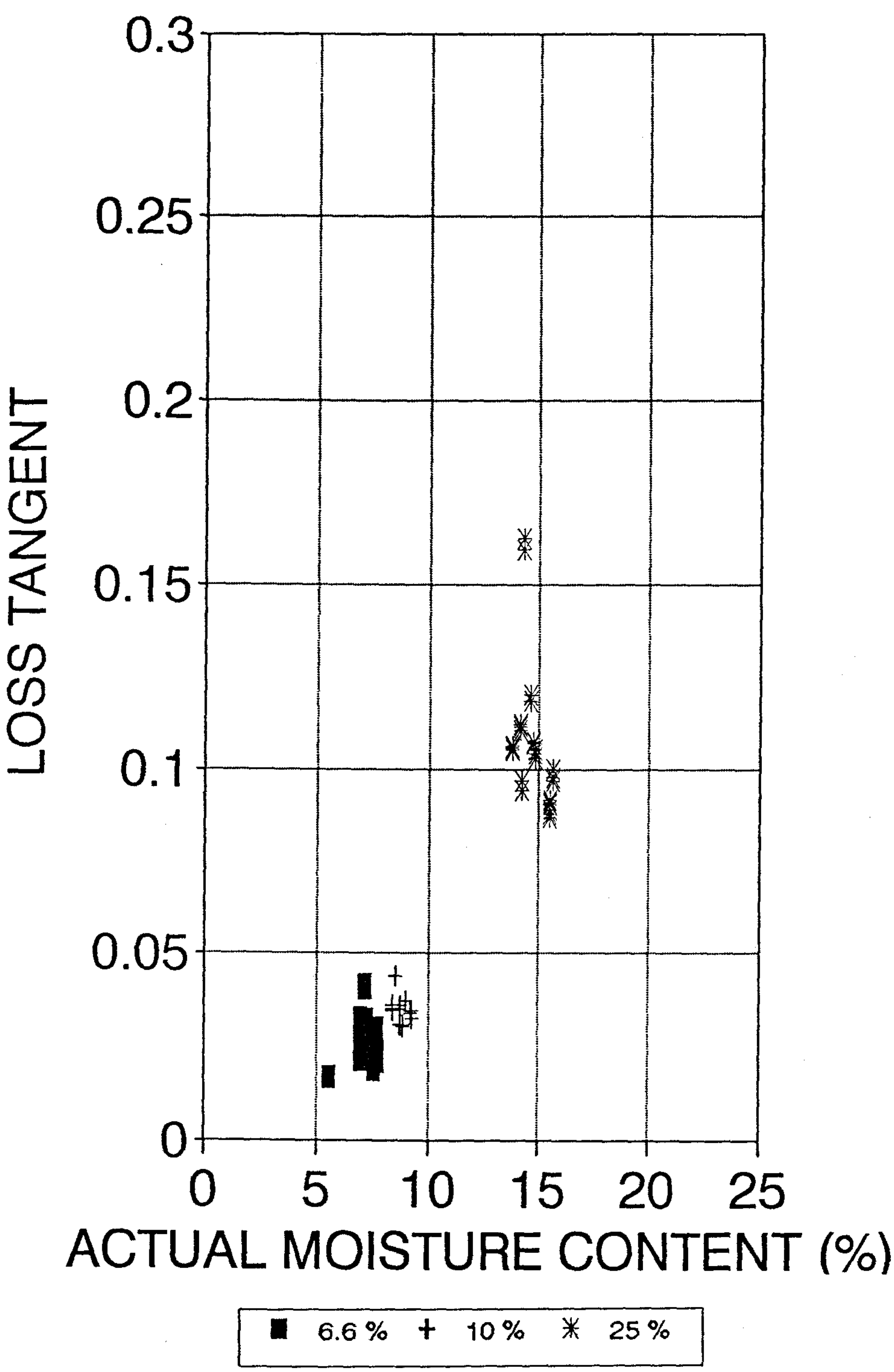

Figure A.4.60. The effect of moisture on the loss tangent of heavy pitch streaks at 1.4 MHz.

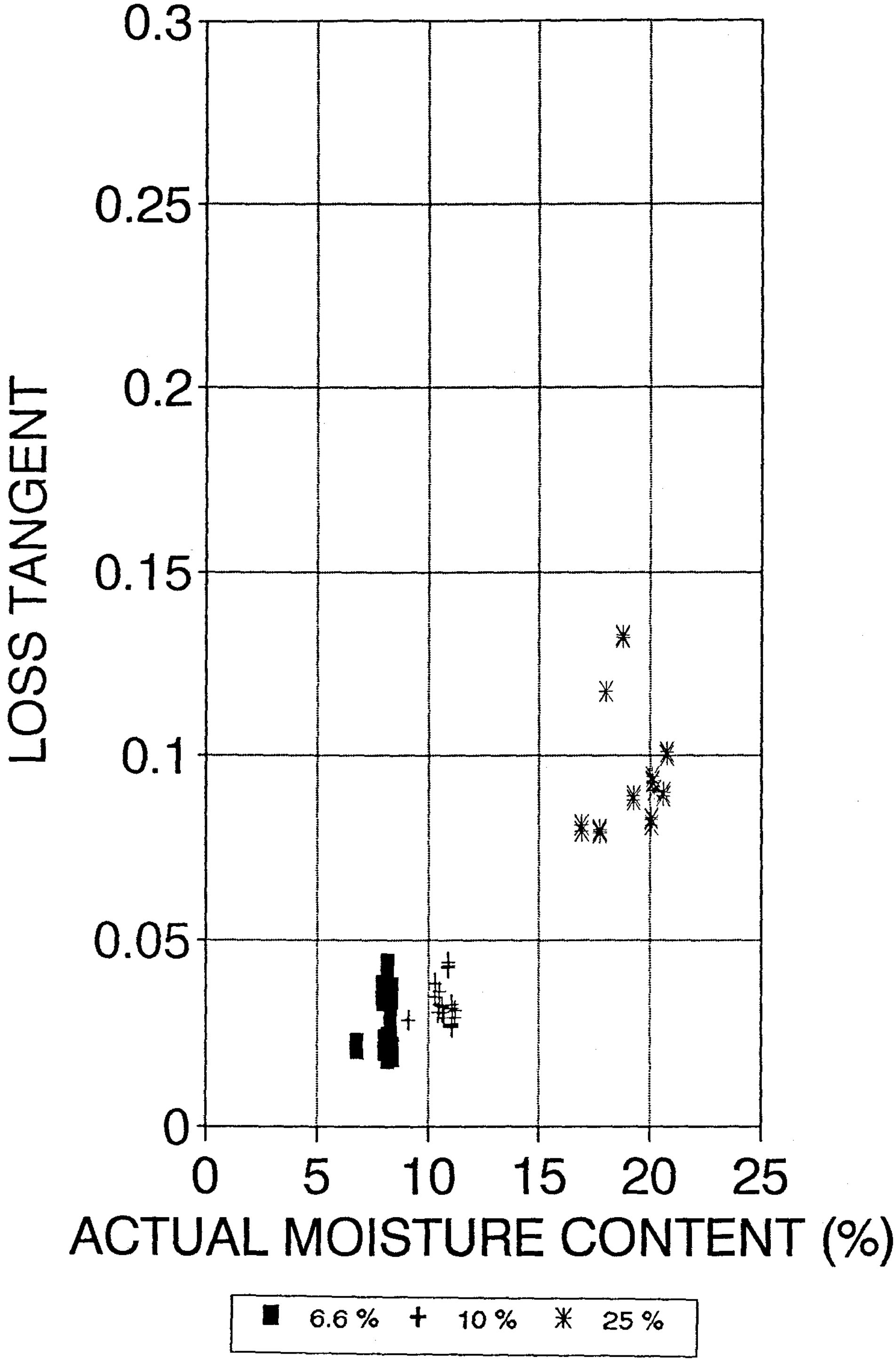

Figure A.4.61. The effect of moisture on the loss tangent of light pitch streaks at 1.4 MHz.

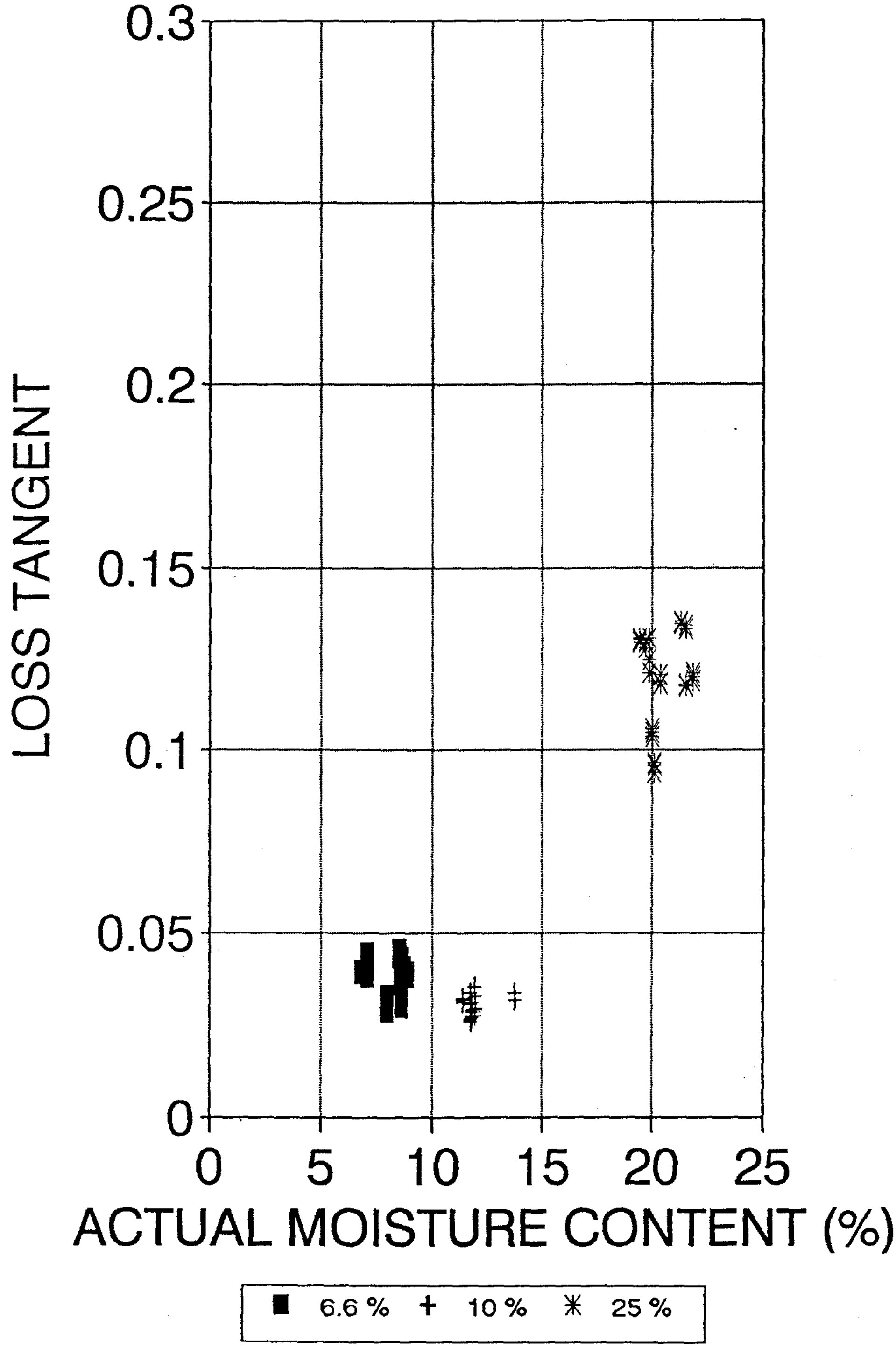

Figure A.4.62. The effect of moisture on the loss tangent of heavy blue stain at 1.4 MHz.

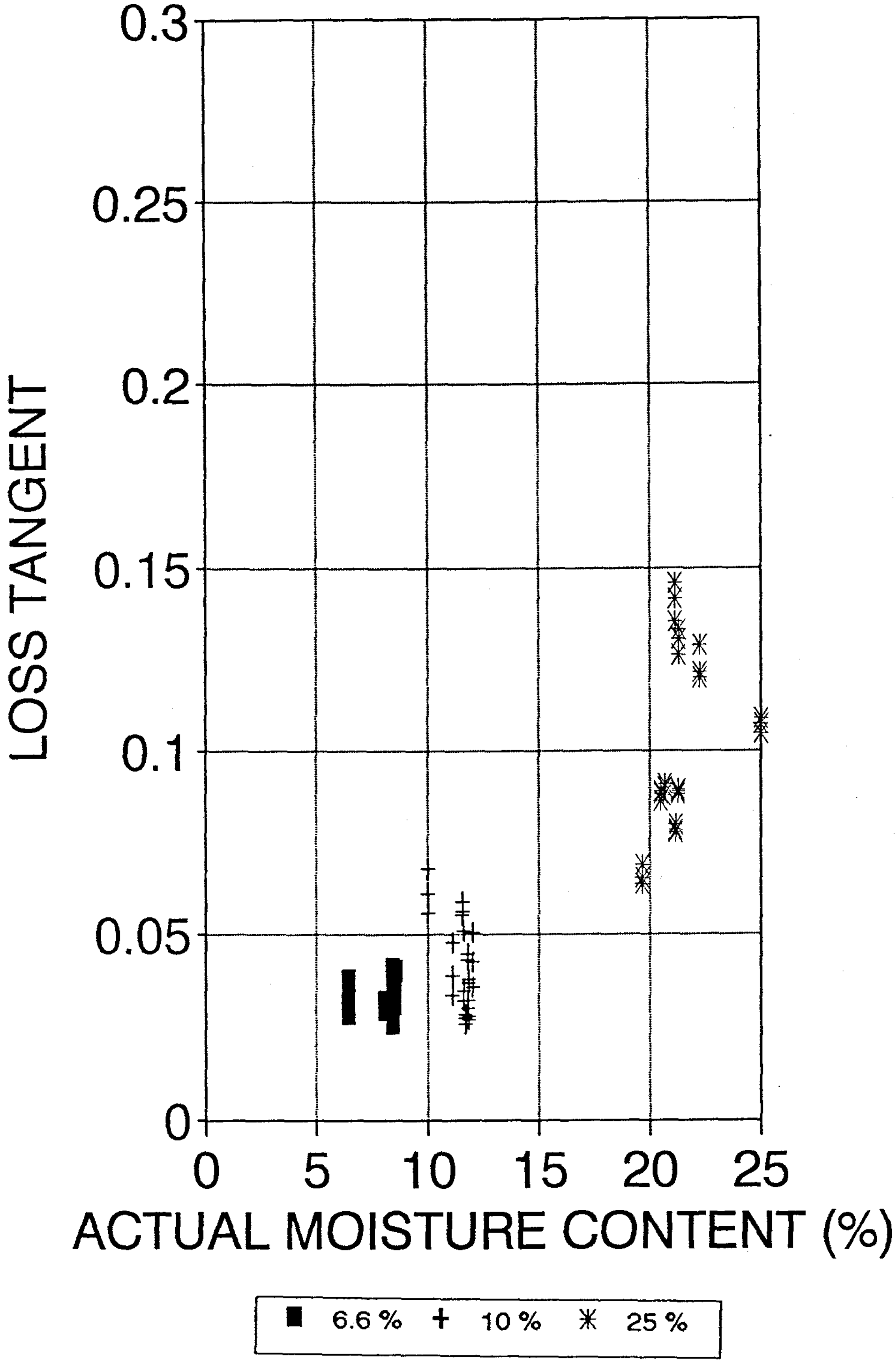

Figure A.4.63. The effect of moisture on the loss tangent of light blue stain at 1.4 MHz.

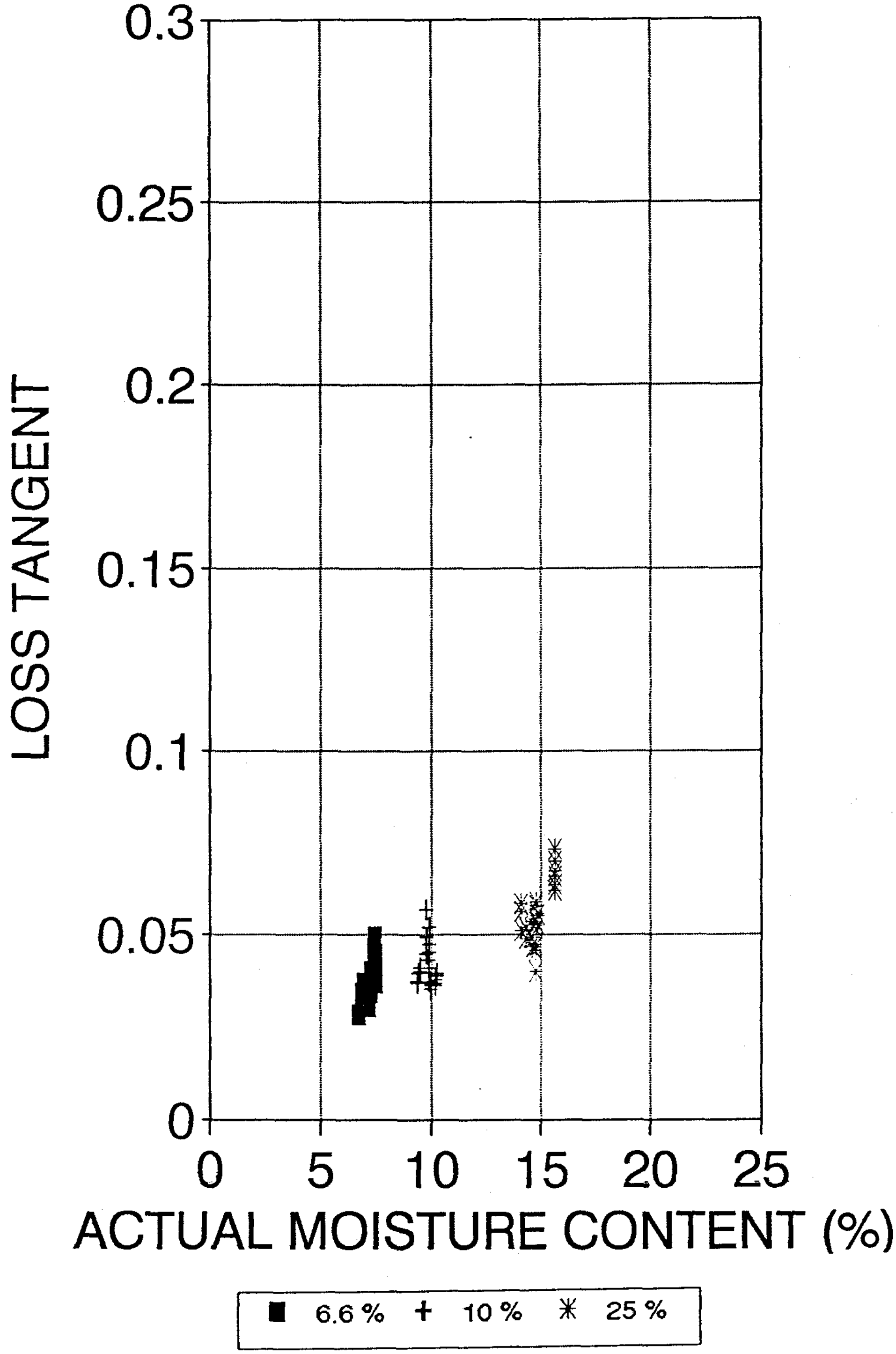

Figure A.4.64. The effect of moisture on the loss tangent of clearwood at 1.4 MHz.

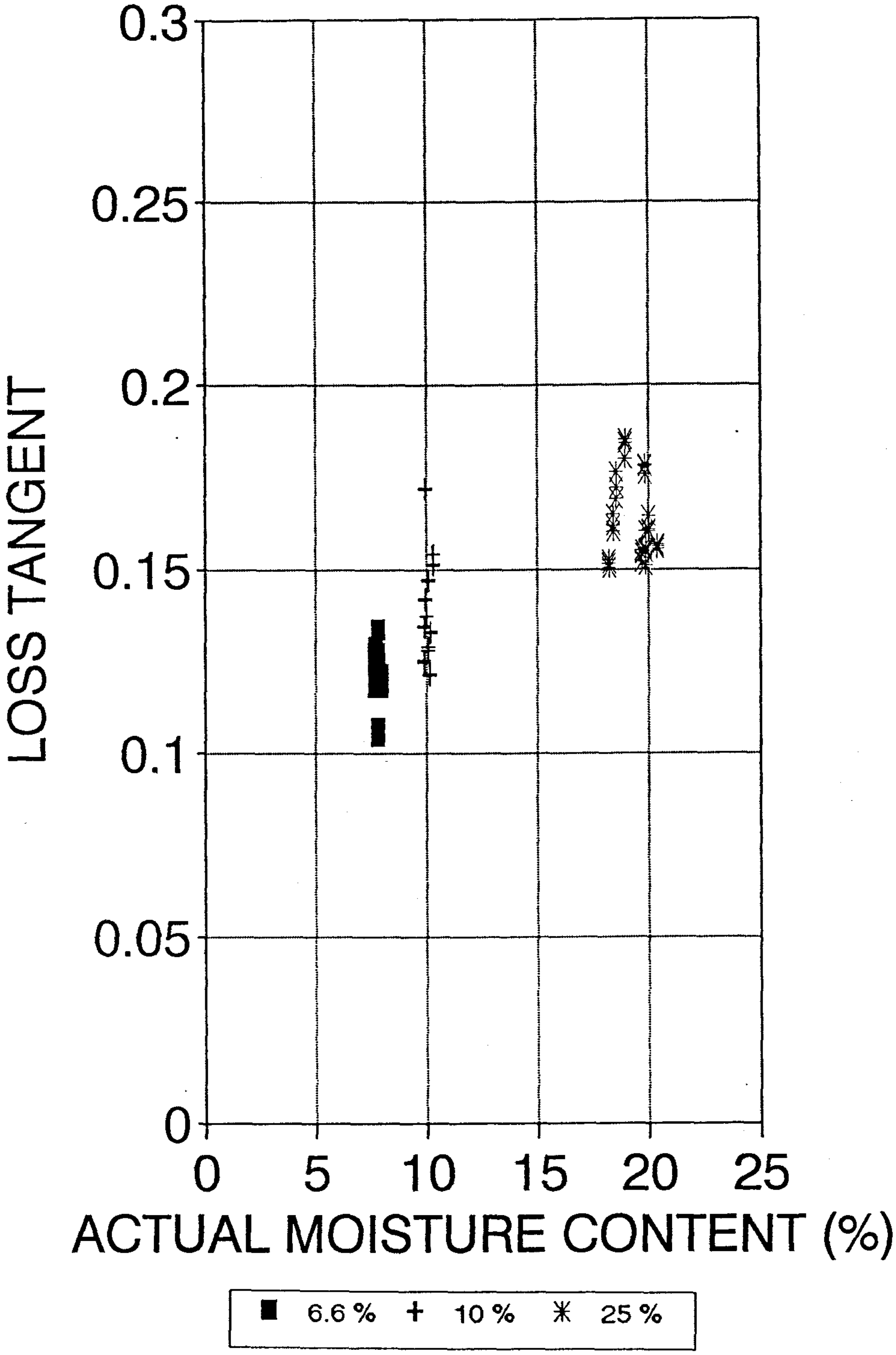

Figure A.4.65. The effect of moisture on the loss tangent of large loose knots at 10 MHz.

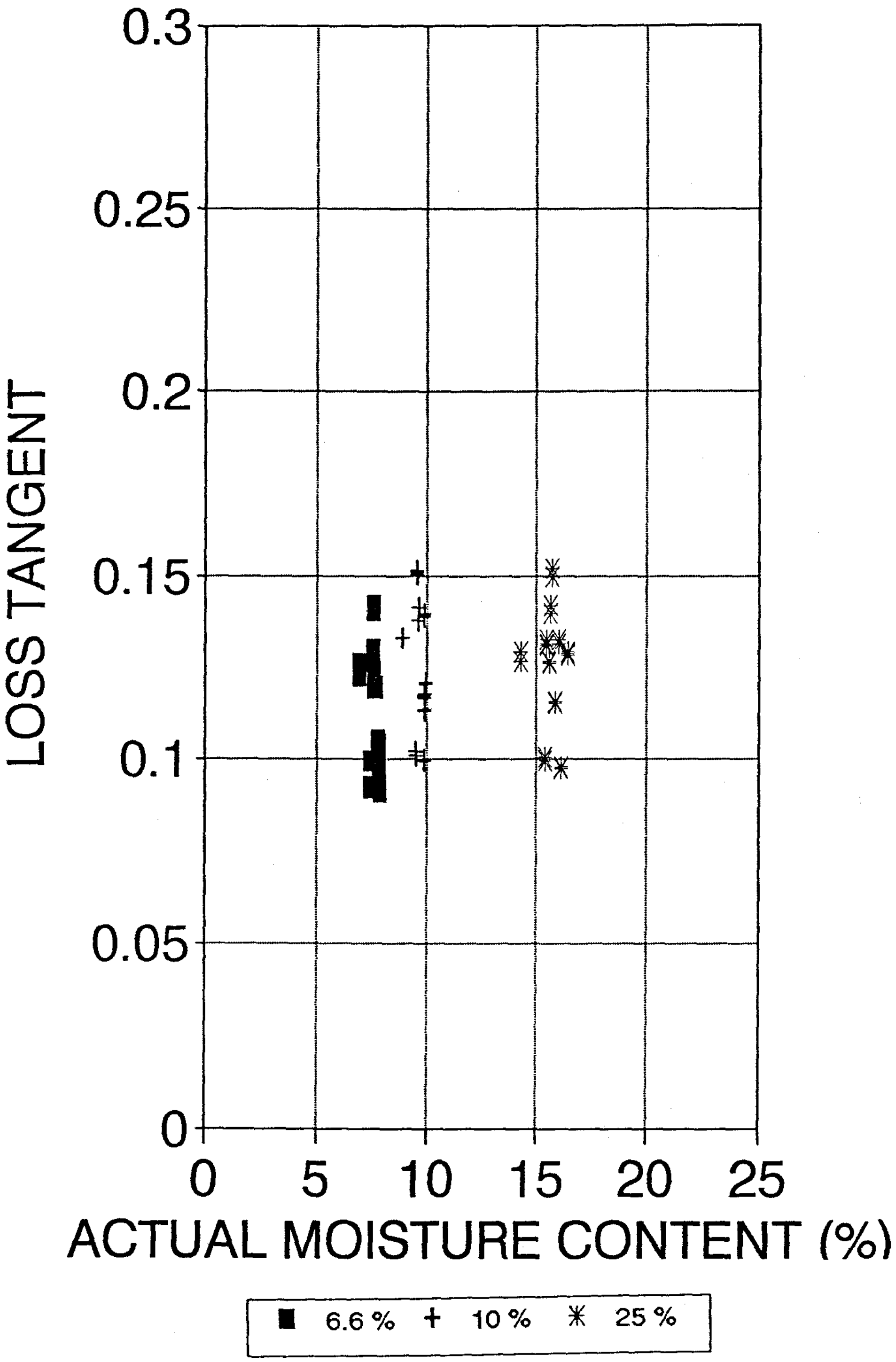

Figure A.4.66. The effect of moisture on the loss tangent of medium loose knots at 10 MHz.

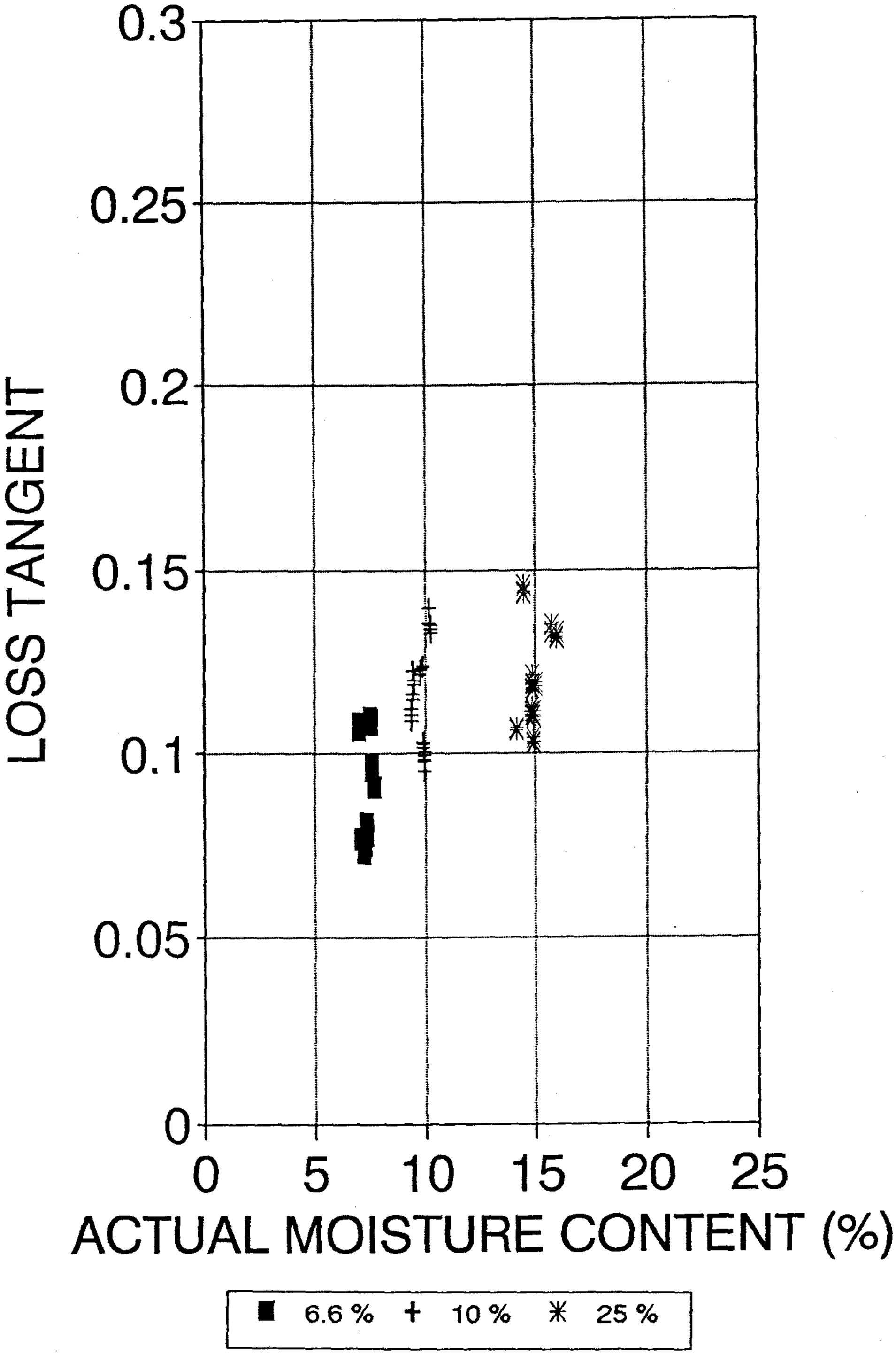

Figure A.4.67. The effect of moisture on the loss tangent of small loose knots at 10 MHz.

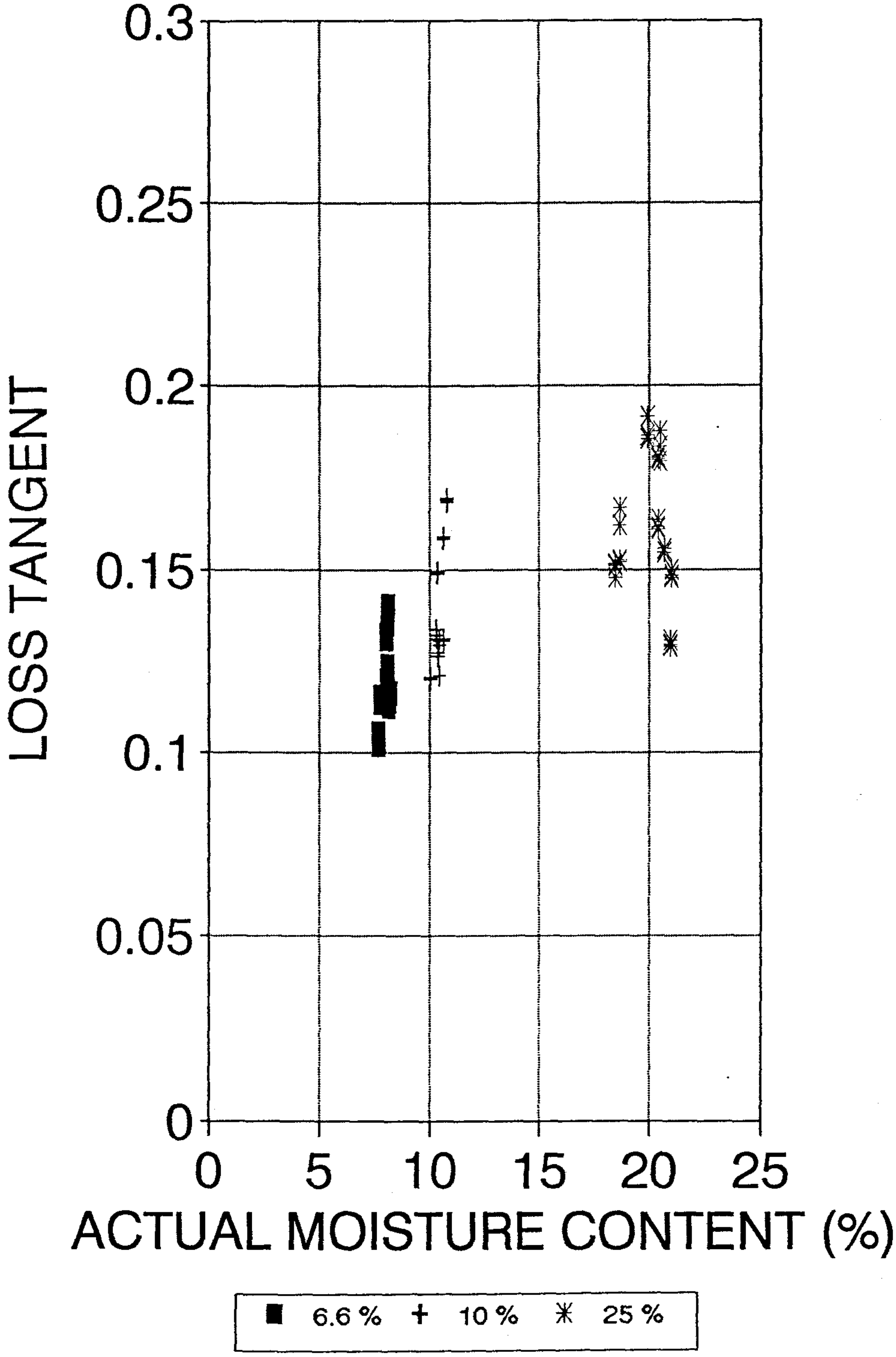

Figure A.4.68. The effect of moisture on the loss tangent of large tight knots at 10 MHz.

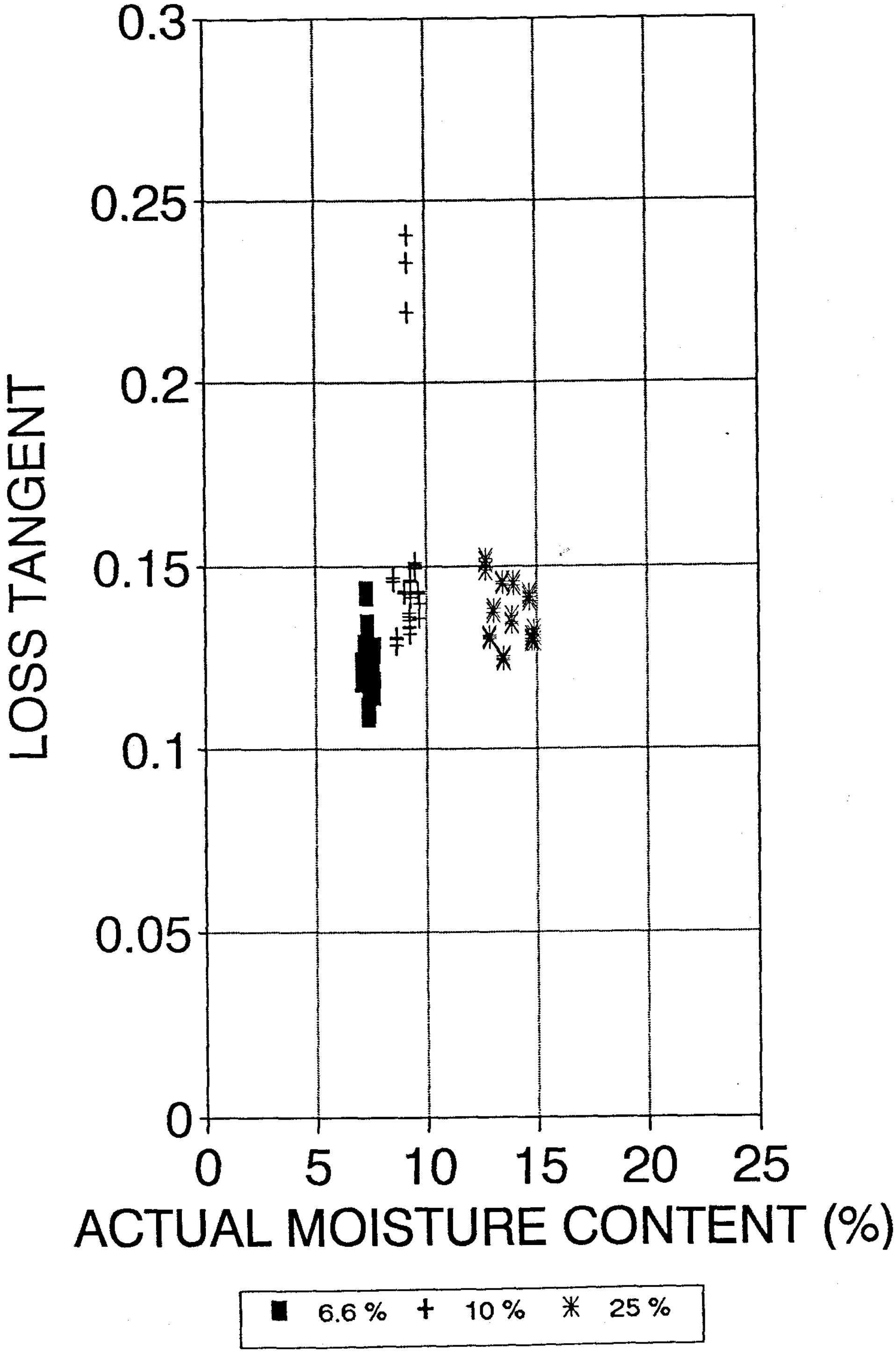

Figure A.4.69. The effect of moisture on the loss tangent of medium tight knots at 10 MHz.

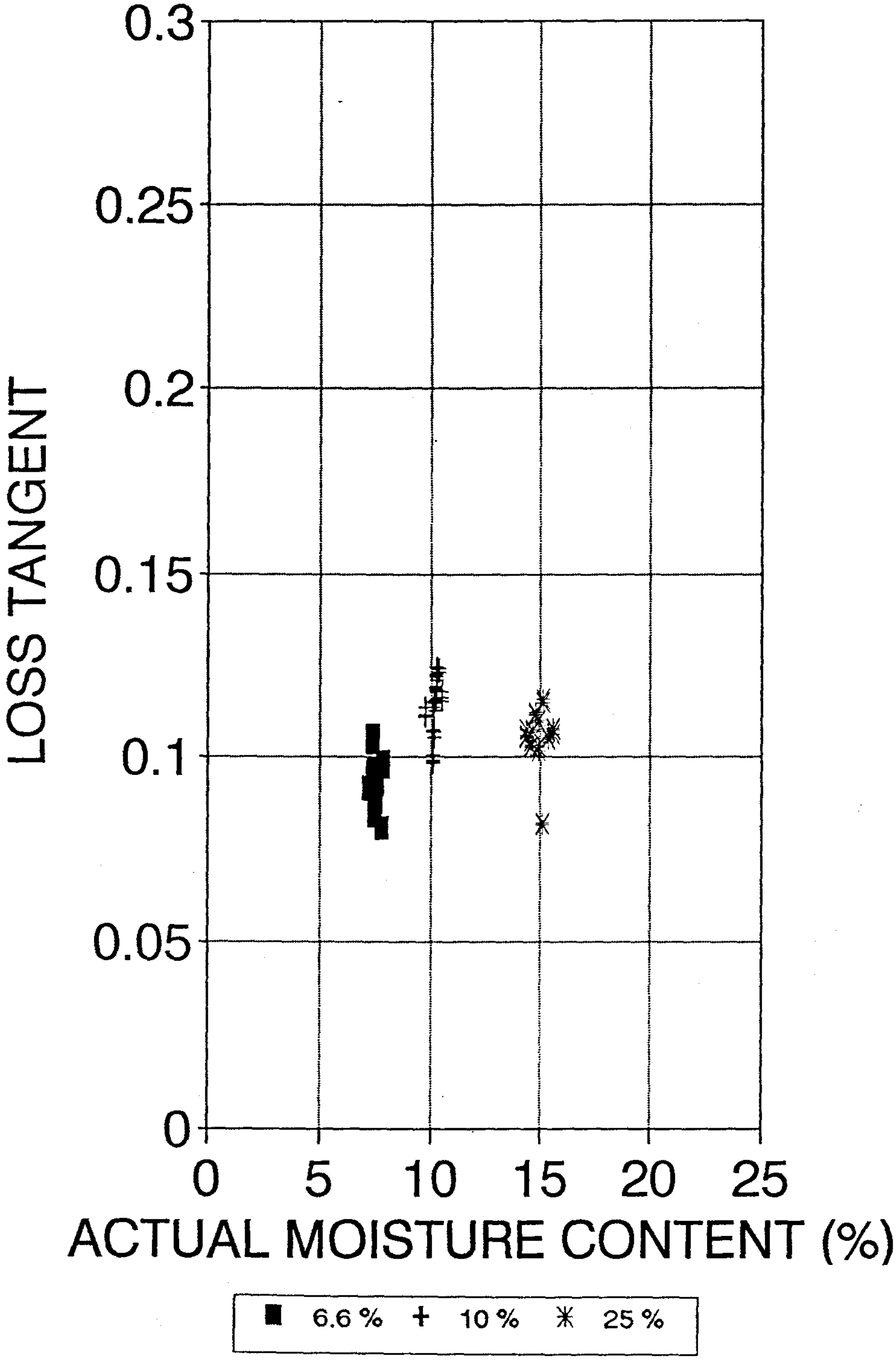

Figure A.4.70. The effect of moisture on the loss tangent of small tight knots at 10 MHz.

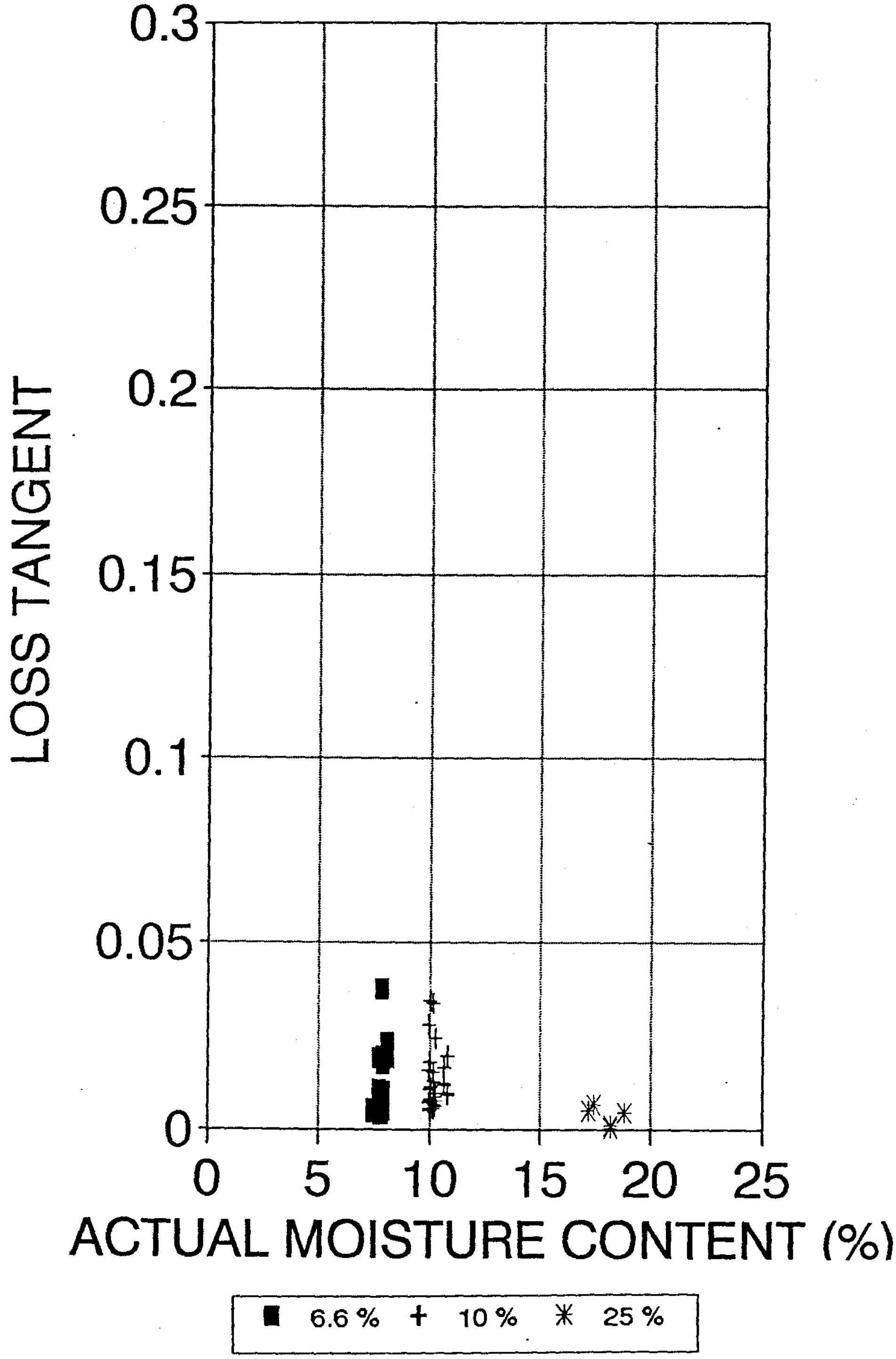

Figure A.4.71. The effect of moisture on the loss tangent of large open holes at 10 MHz.

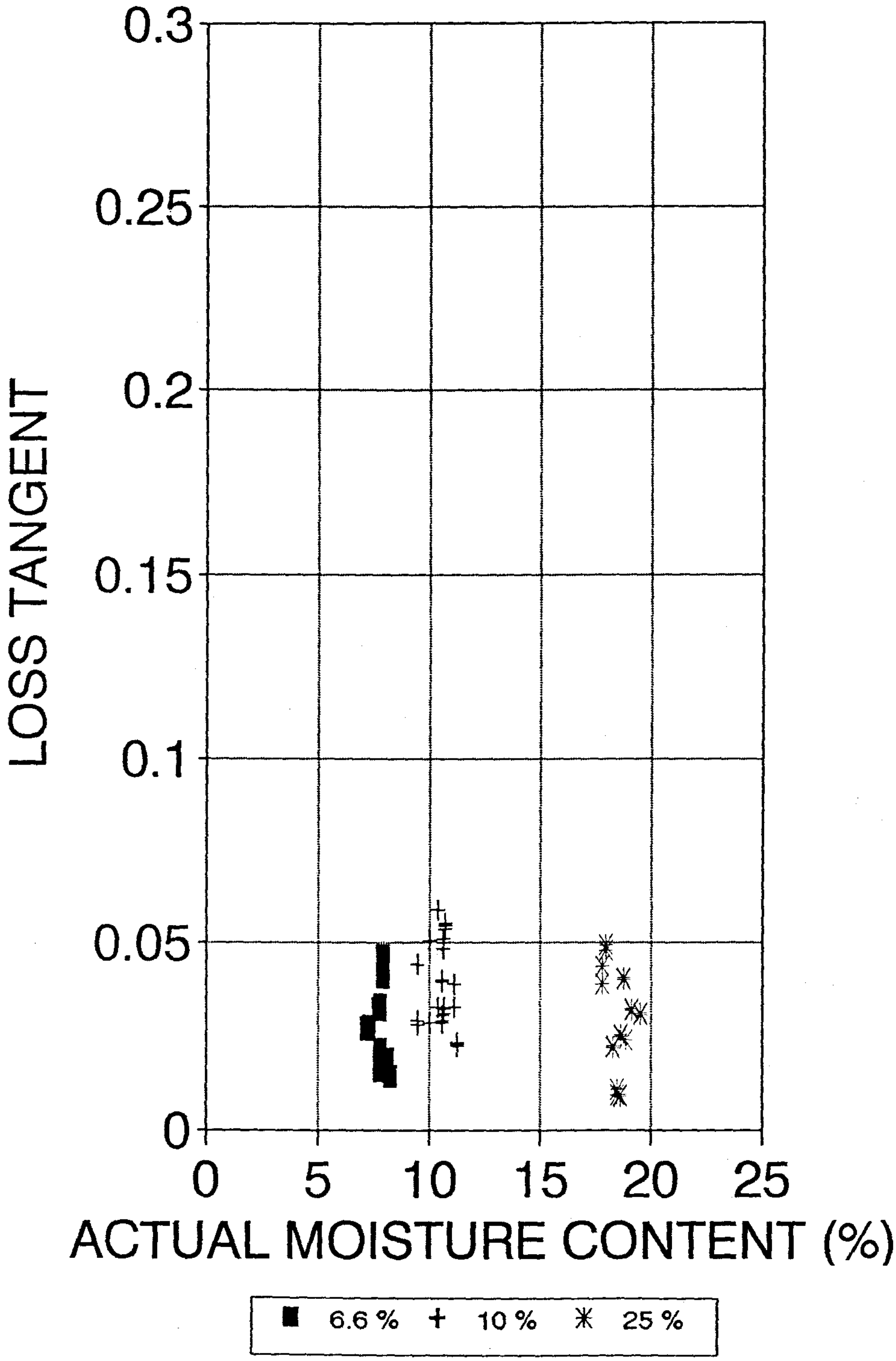

Figure A.4.72. The effect of moisture on the loss tangent of medium open holes at 10 MHz.

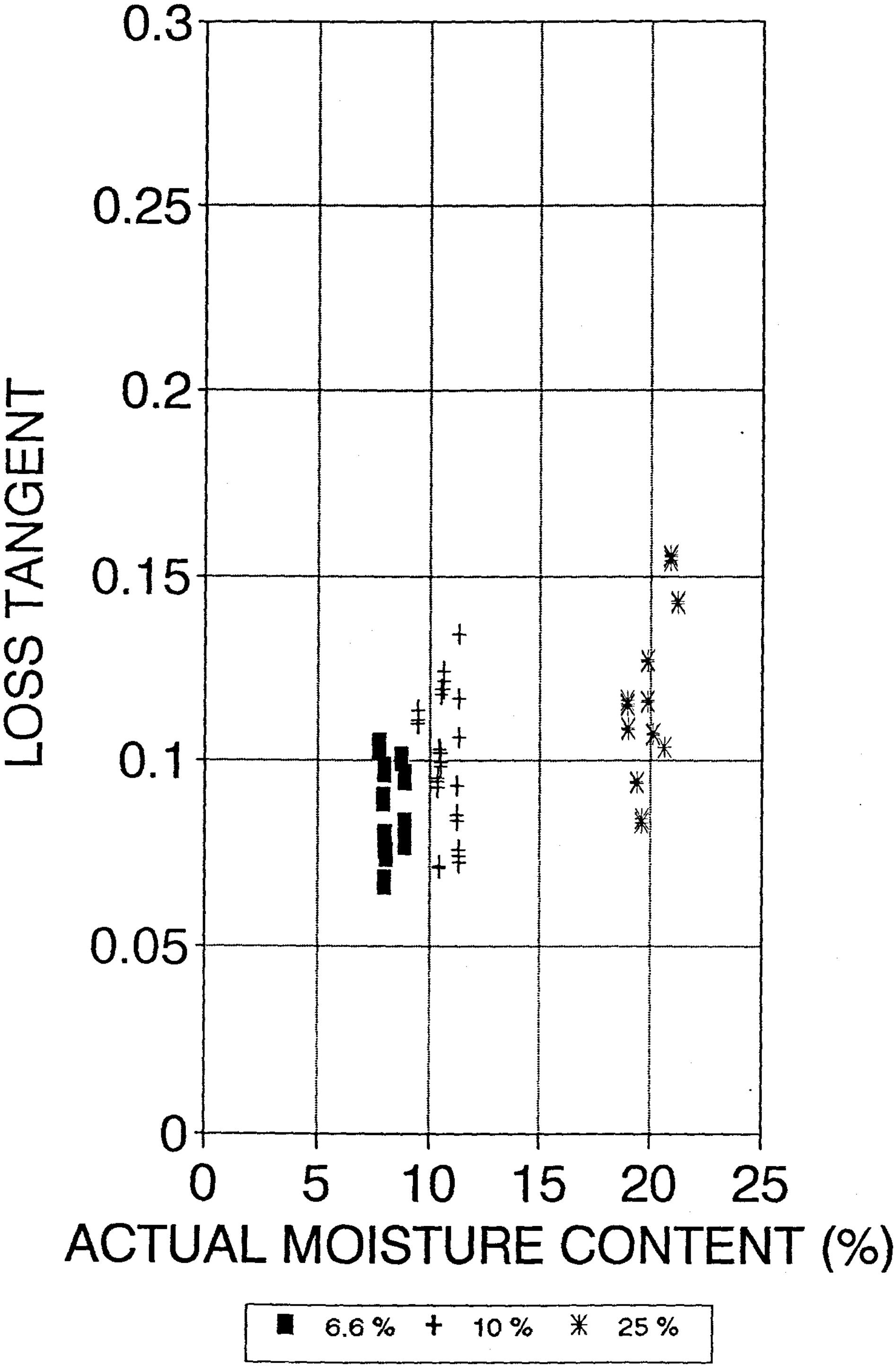

Figure A.4.73. The effect of moisture on the loss tangent of small open holes at 10 MHz.

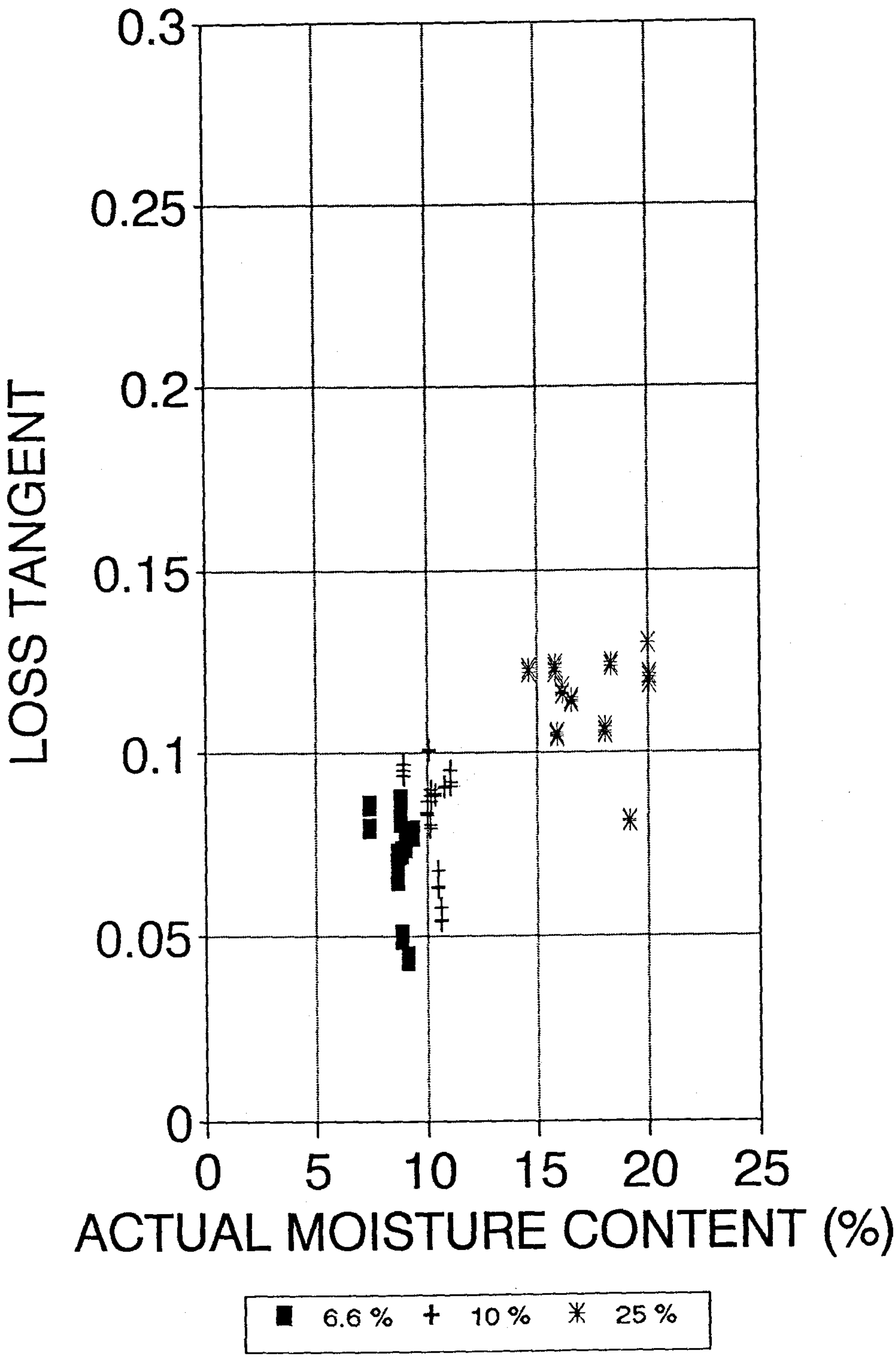

Figure A.4.74. The effect of moisture on the loss tangent of large pitch pockets at 10 MHz.

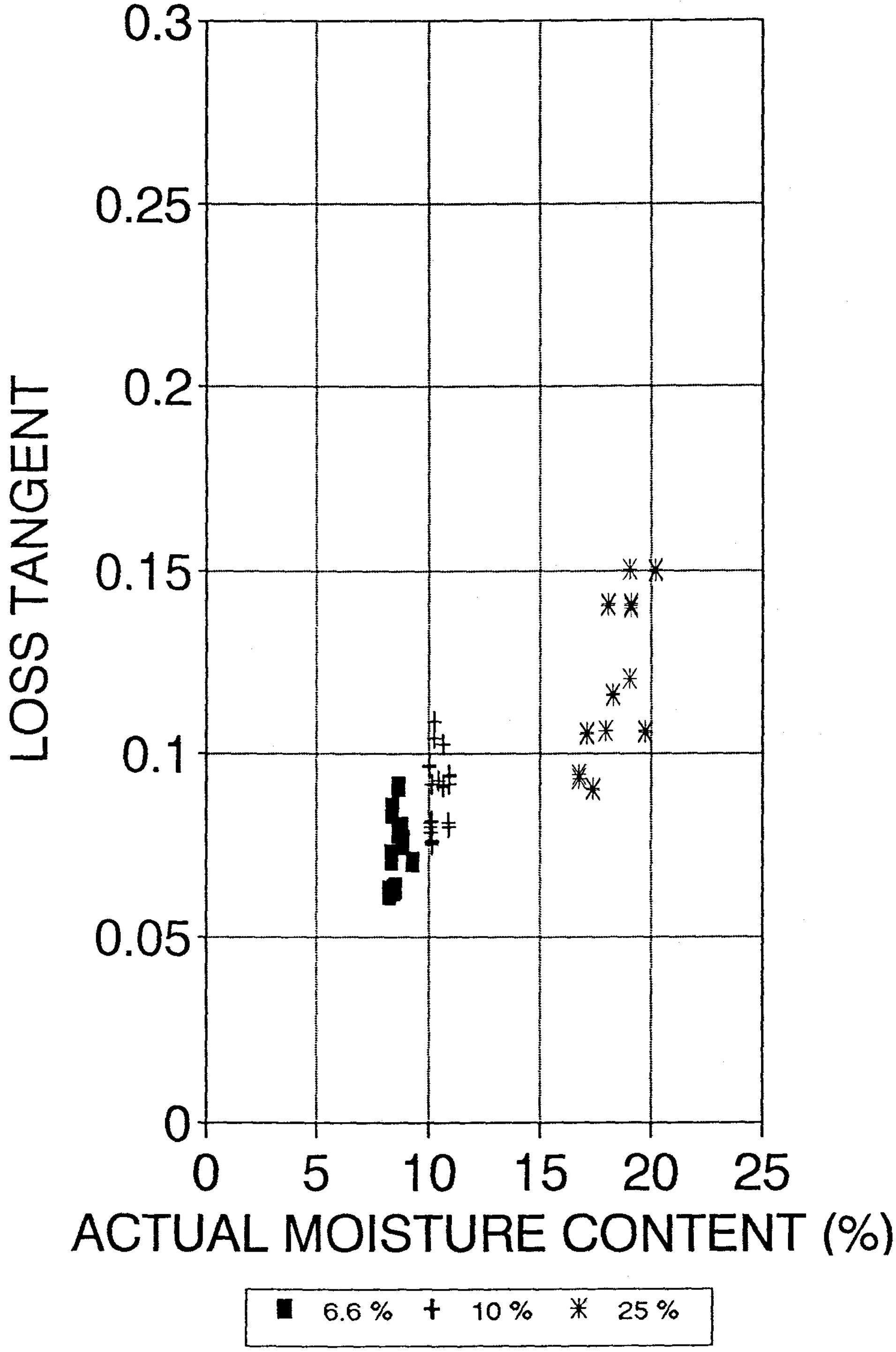

Figure A.4.75. The effect of moisture on the loss tangent of small pitch pockets at 10 MHz.

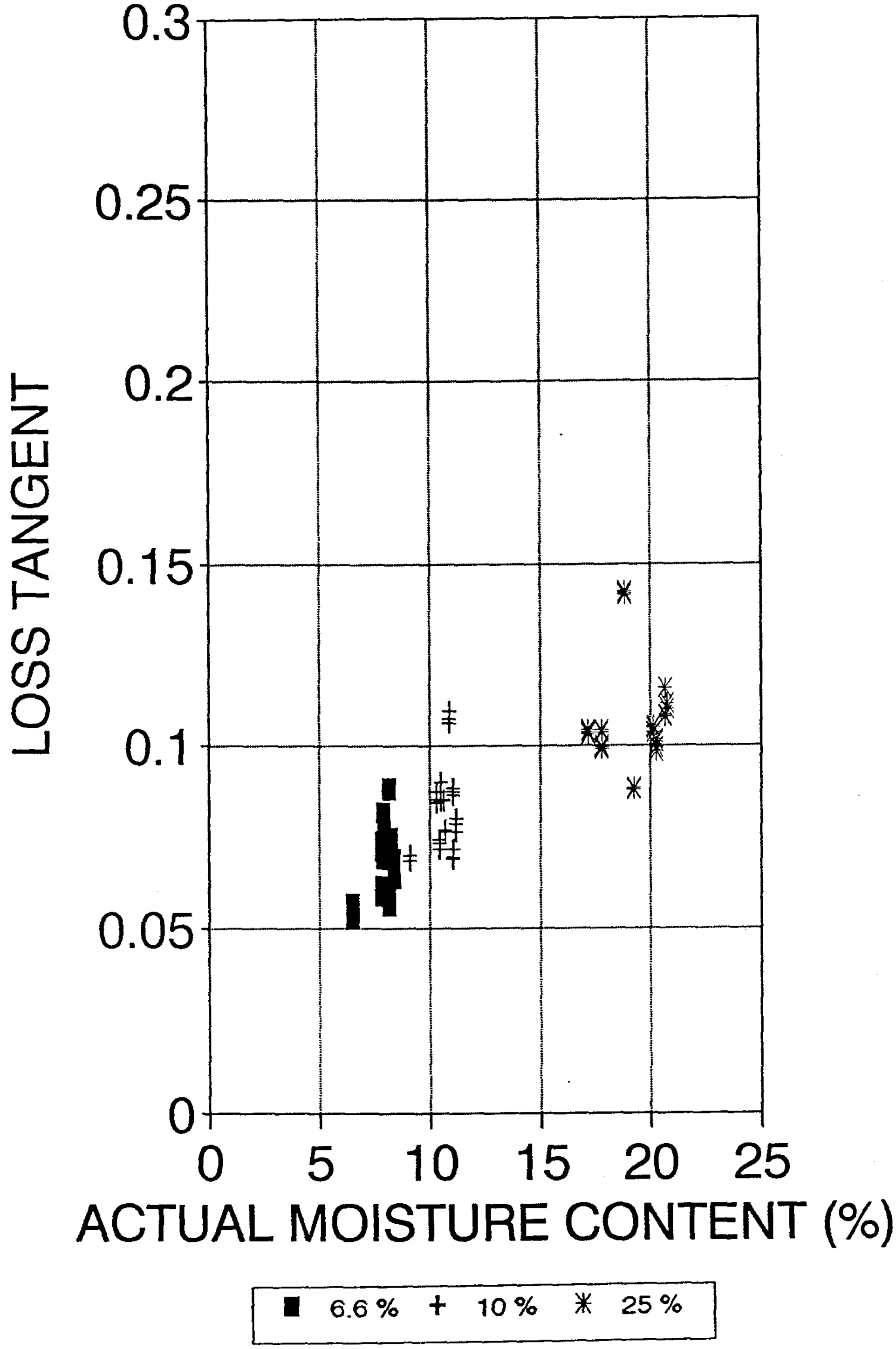

Figure A.4.76. The effect of moisture on the loss tangent of heavy pitch streaks at 10 MHz.

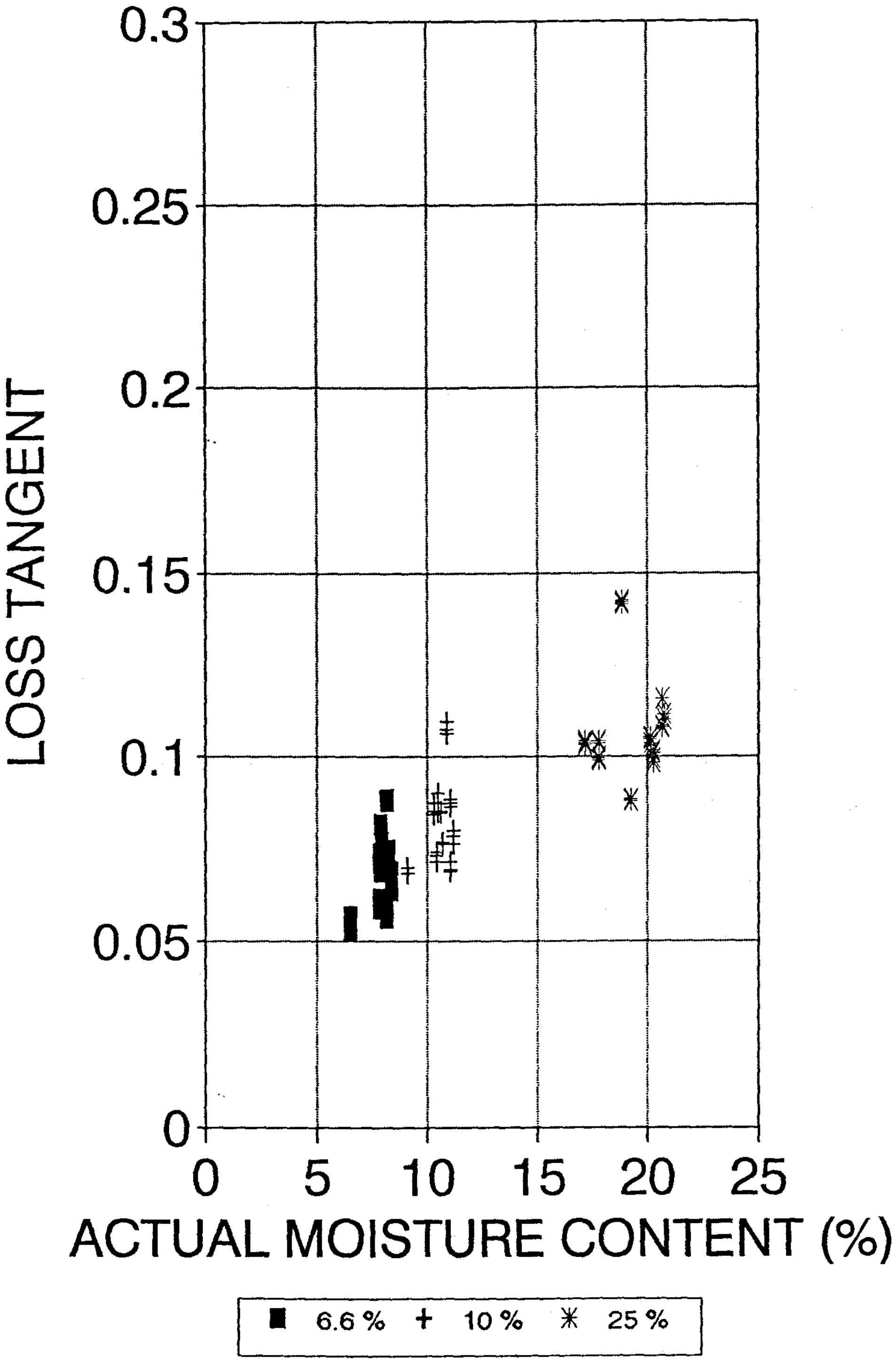

Figure A.4.77. The effect of moisture on the loss tangent of light pitch streaks at 10 MHz.

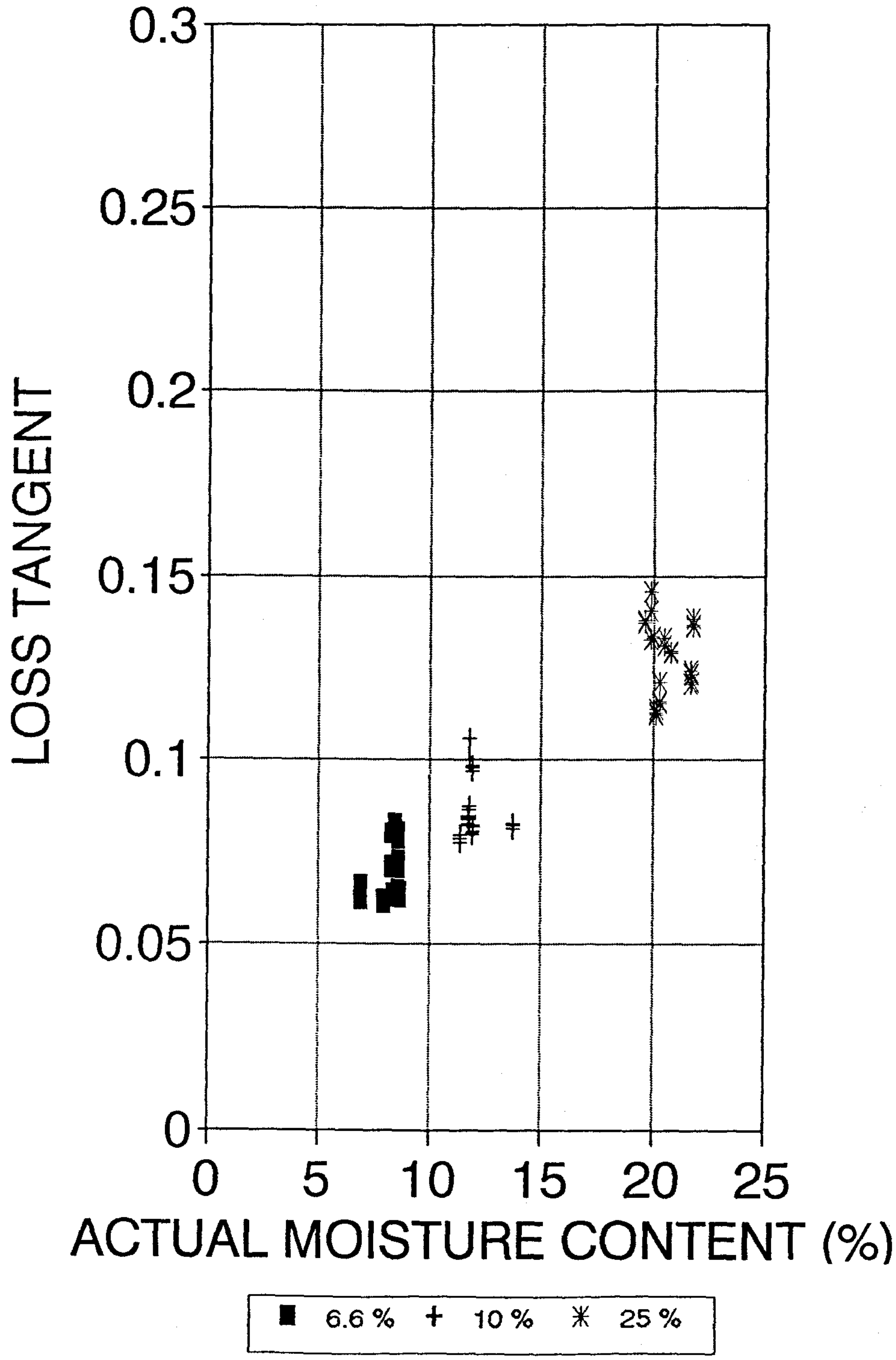

Figure A.4.78. The effect of moisture on the loss tangent of heavy blue stain at 10 MHz.

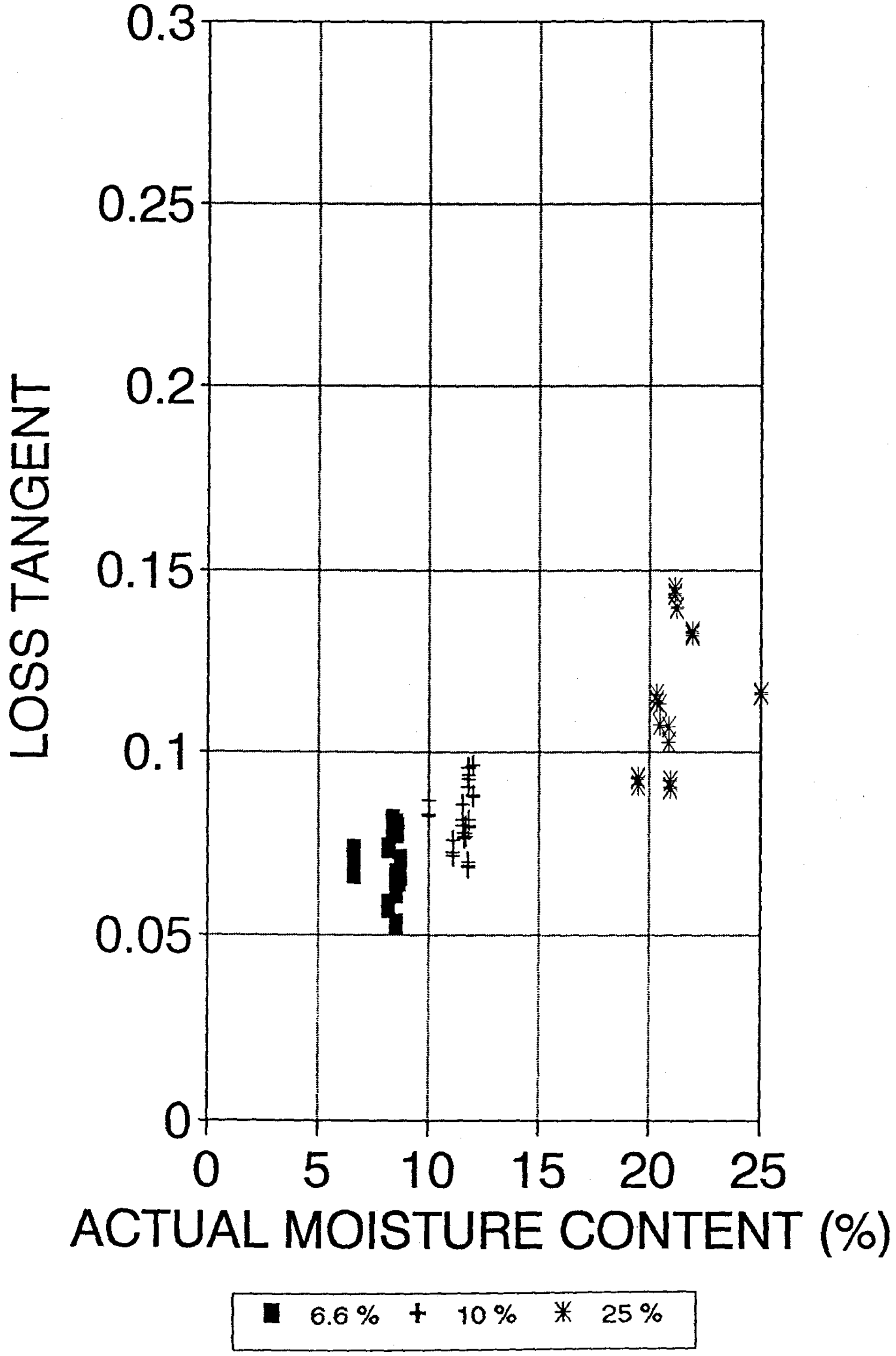

Figure A.4.79. The effect of moisture on the loss tangent of light blue stain at 10 MHz.

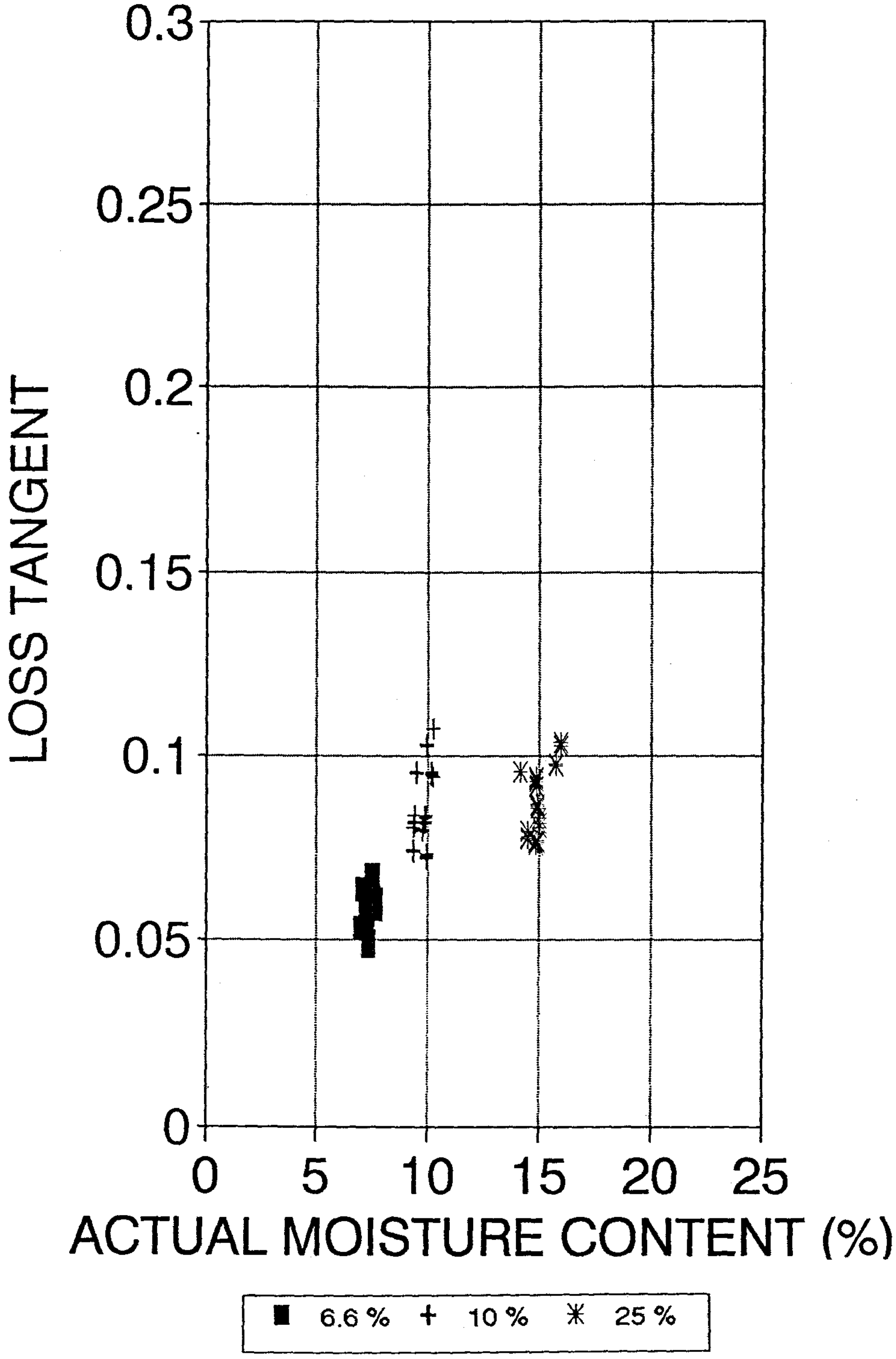

Figure A.4.80. The effect of moisture on the loss tangent of clearwood at 10 MHz.

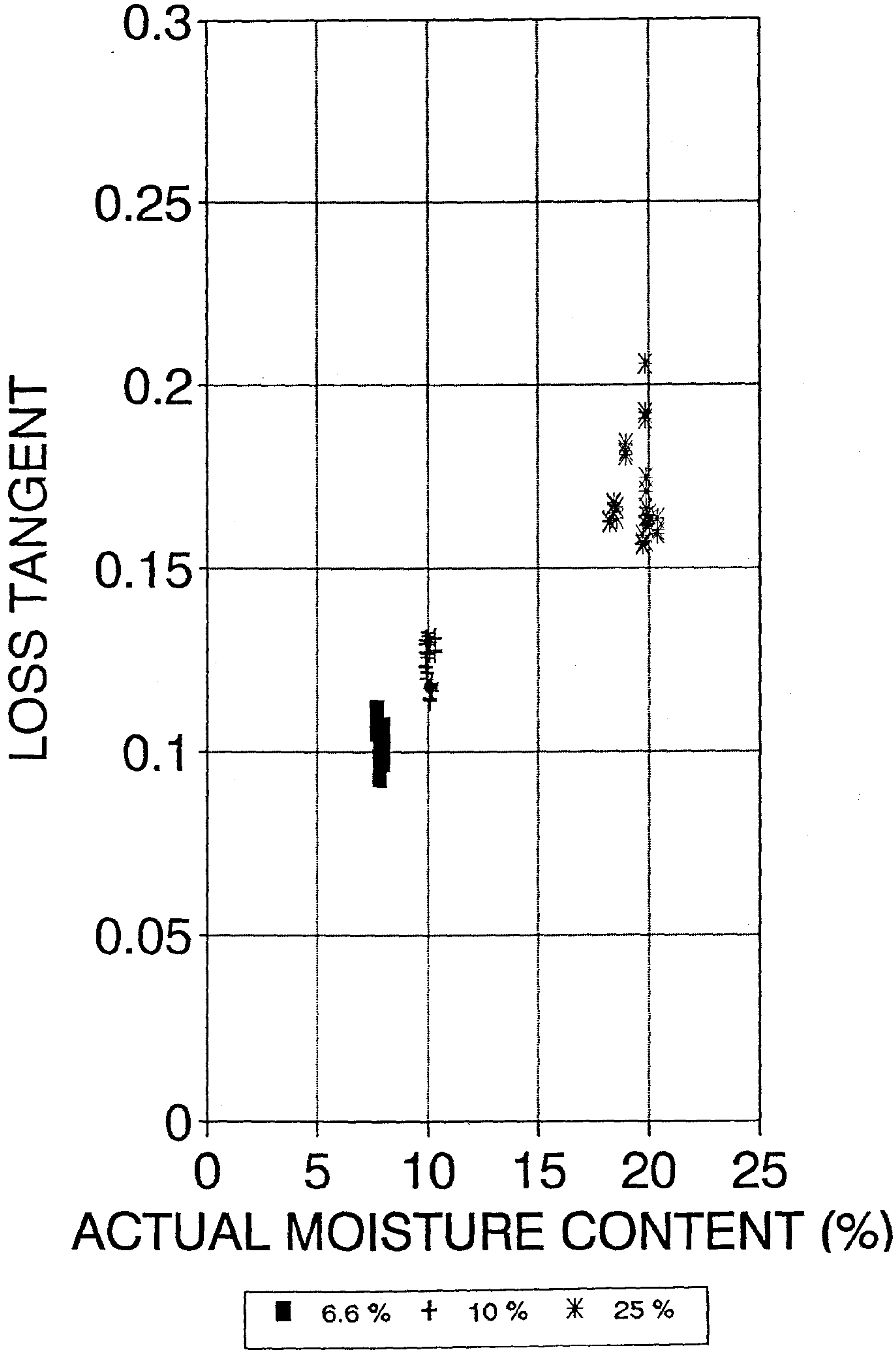

Figure A.4.81. The effect of moisture on the loss tangent of large loose knots at 20 MHz.

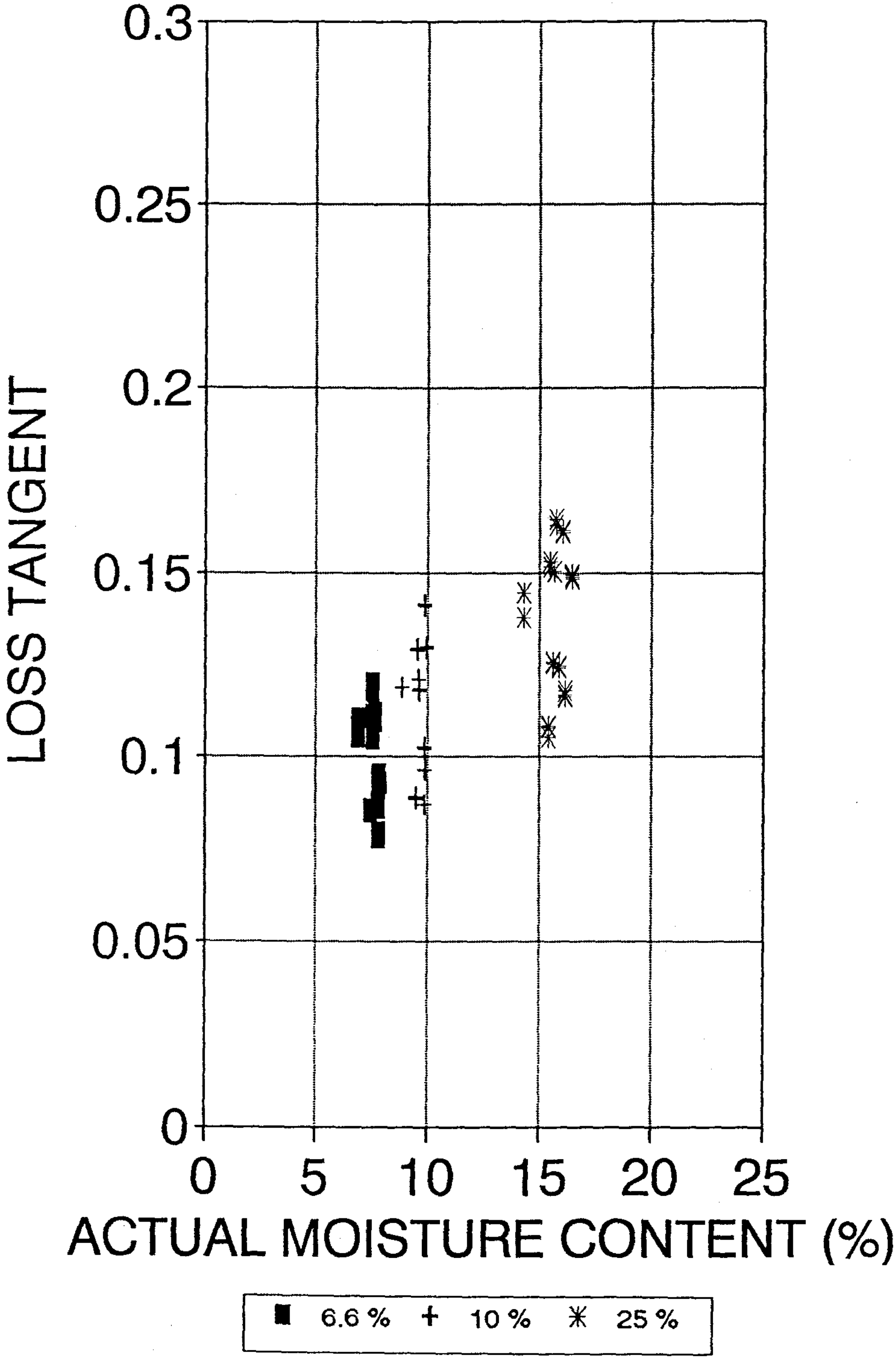

Figure A.4.82. The effect of moisture on the loss tangent of medium loose knots at 20 MHz.

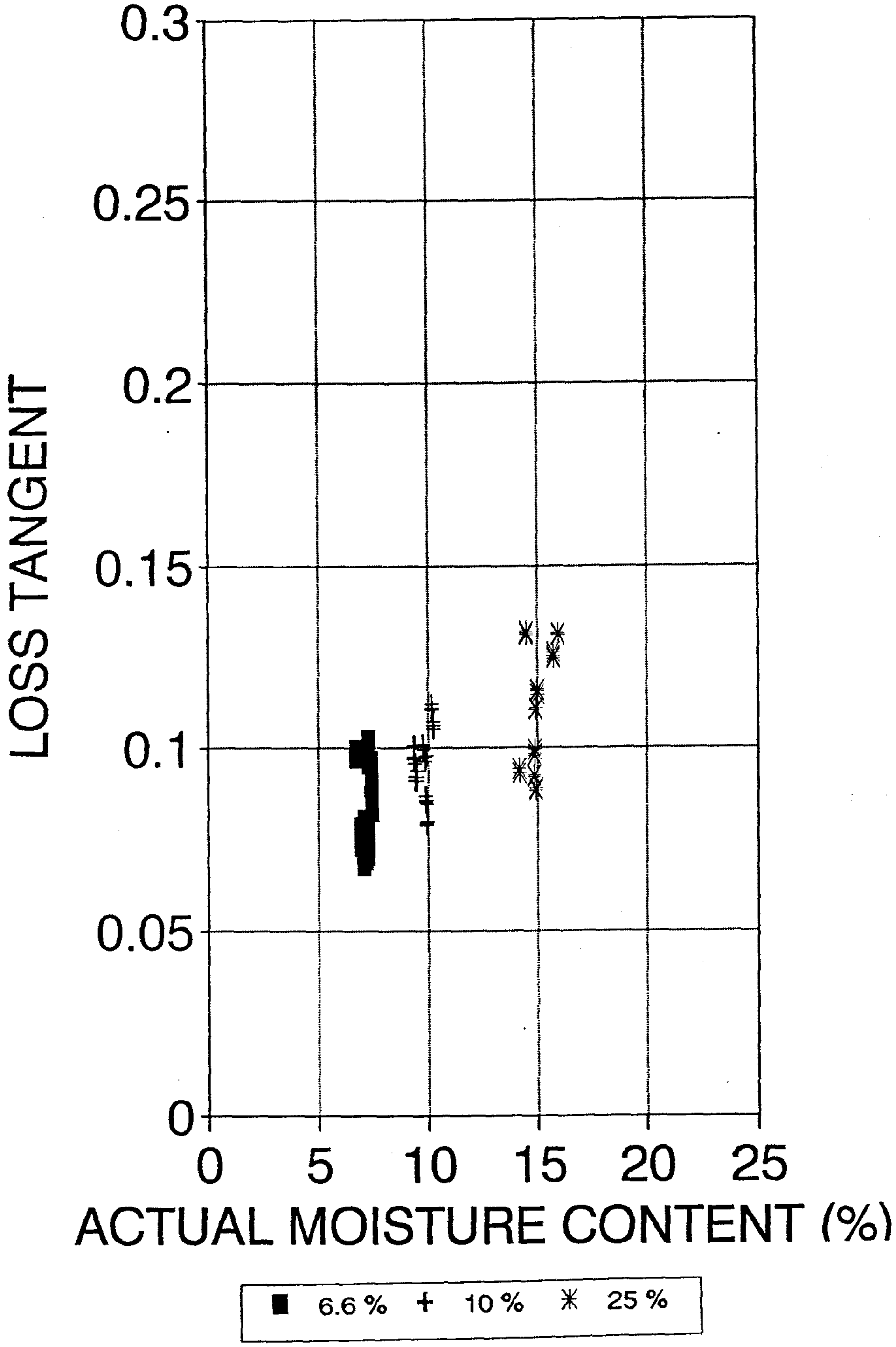

Figure A.4.83. The effect of moisture on the loss tangent of small loose knots at 20 MHz.

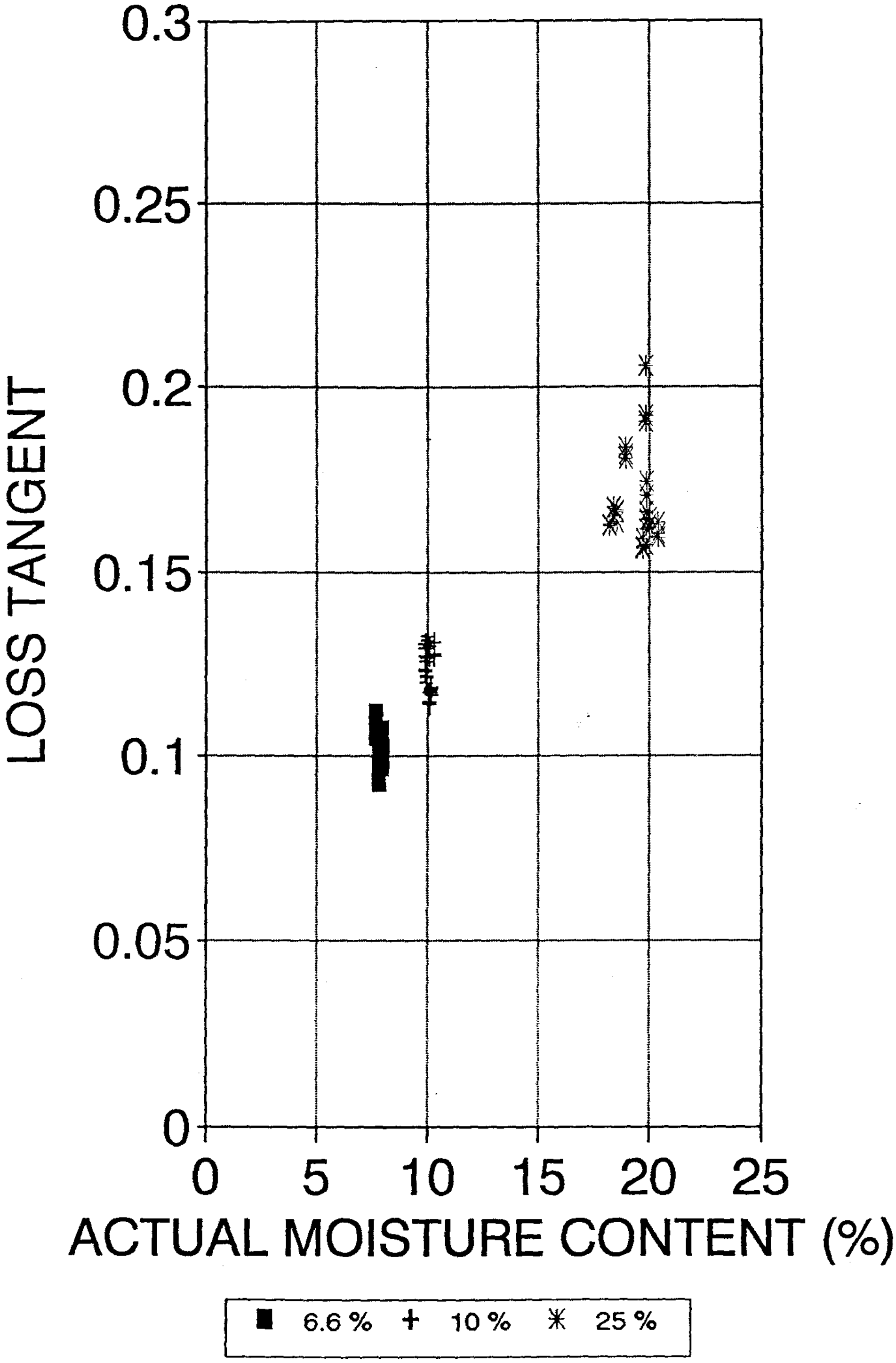

Figure A.4.84. The effect of moisture on the loss tangent of large tight knots at 20 MHz.

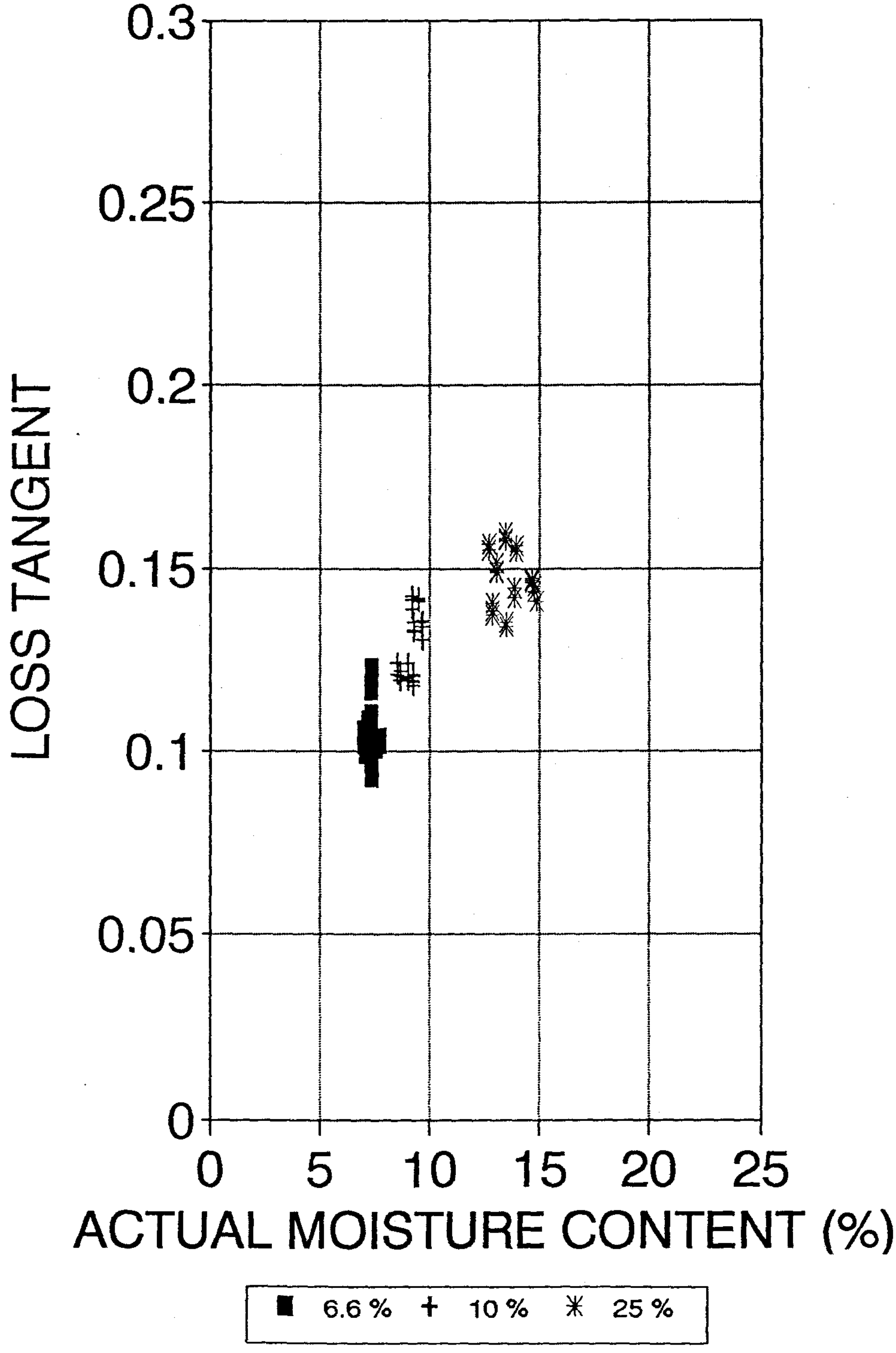

Figure A.4.85. The effect of moisture on the loss tangent of medium tight knots at 20 MHz.

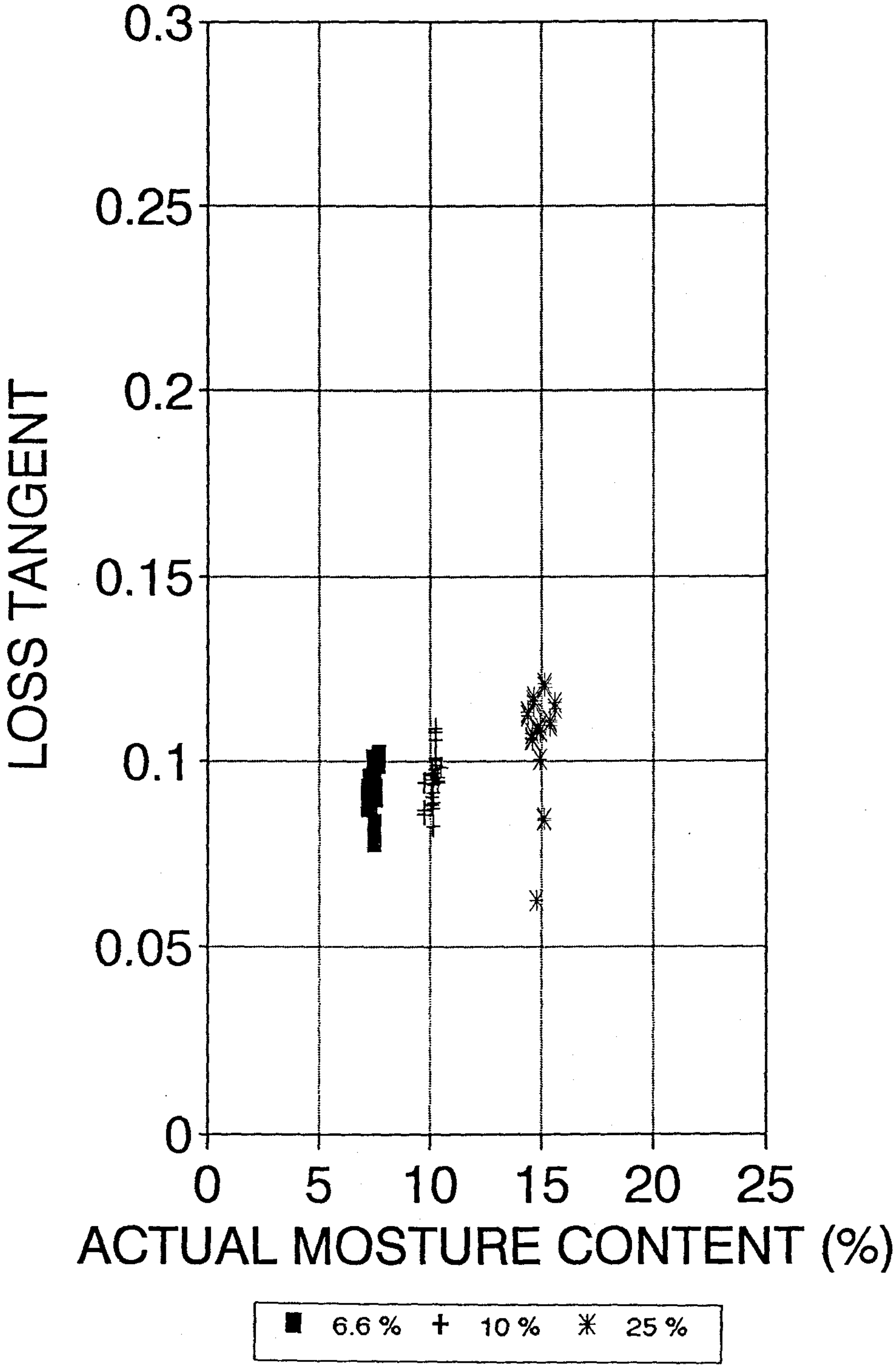

Figure A.4.86. The effect of moisture on the loss tangent of small tight knots at 20 MHz.

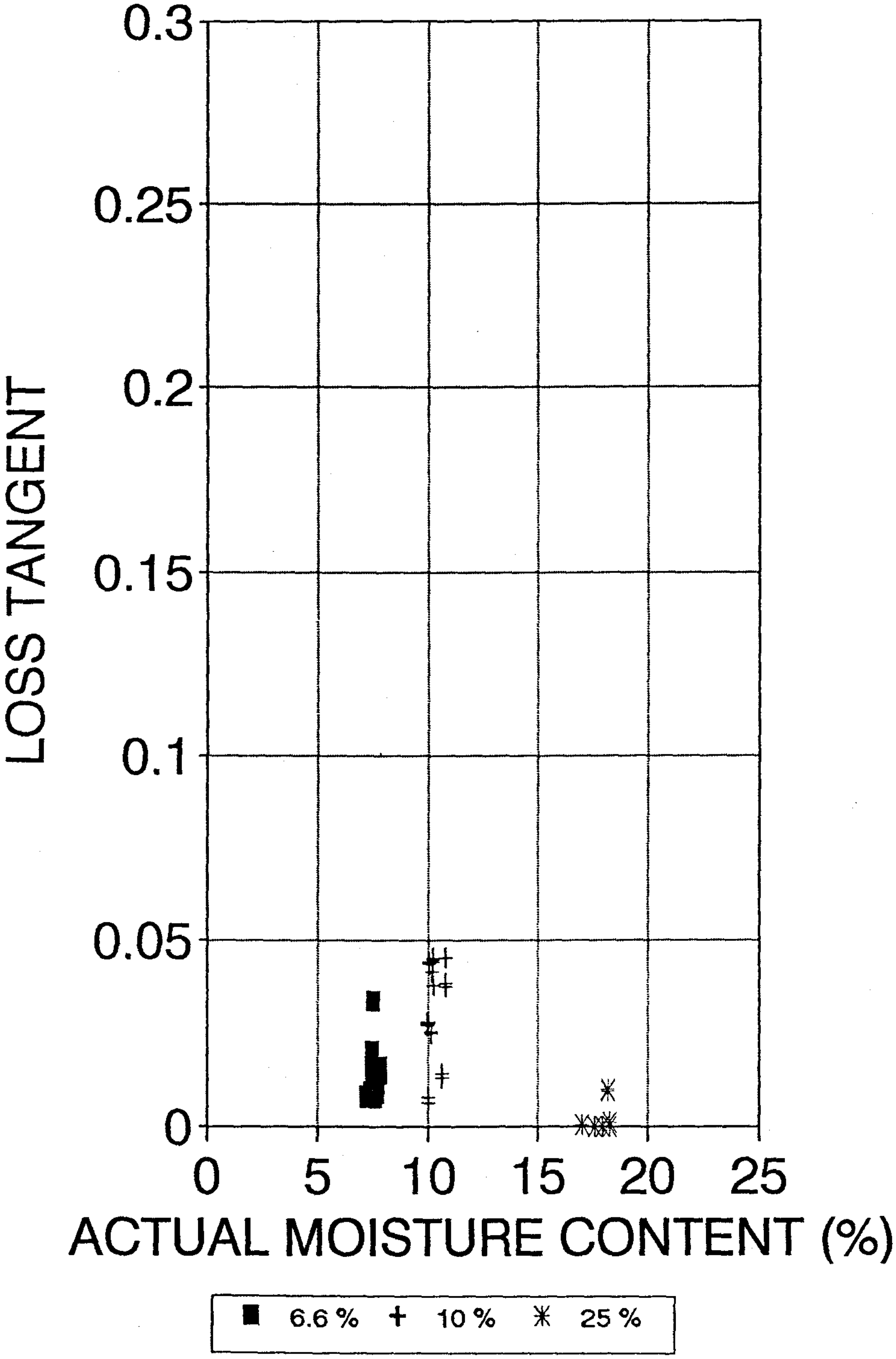

Figure A.4.87. The effect of moisture on the loss tangent of large open holes at 20 MHz.

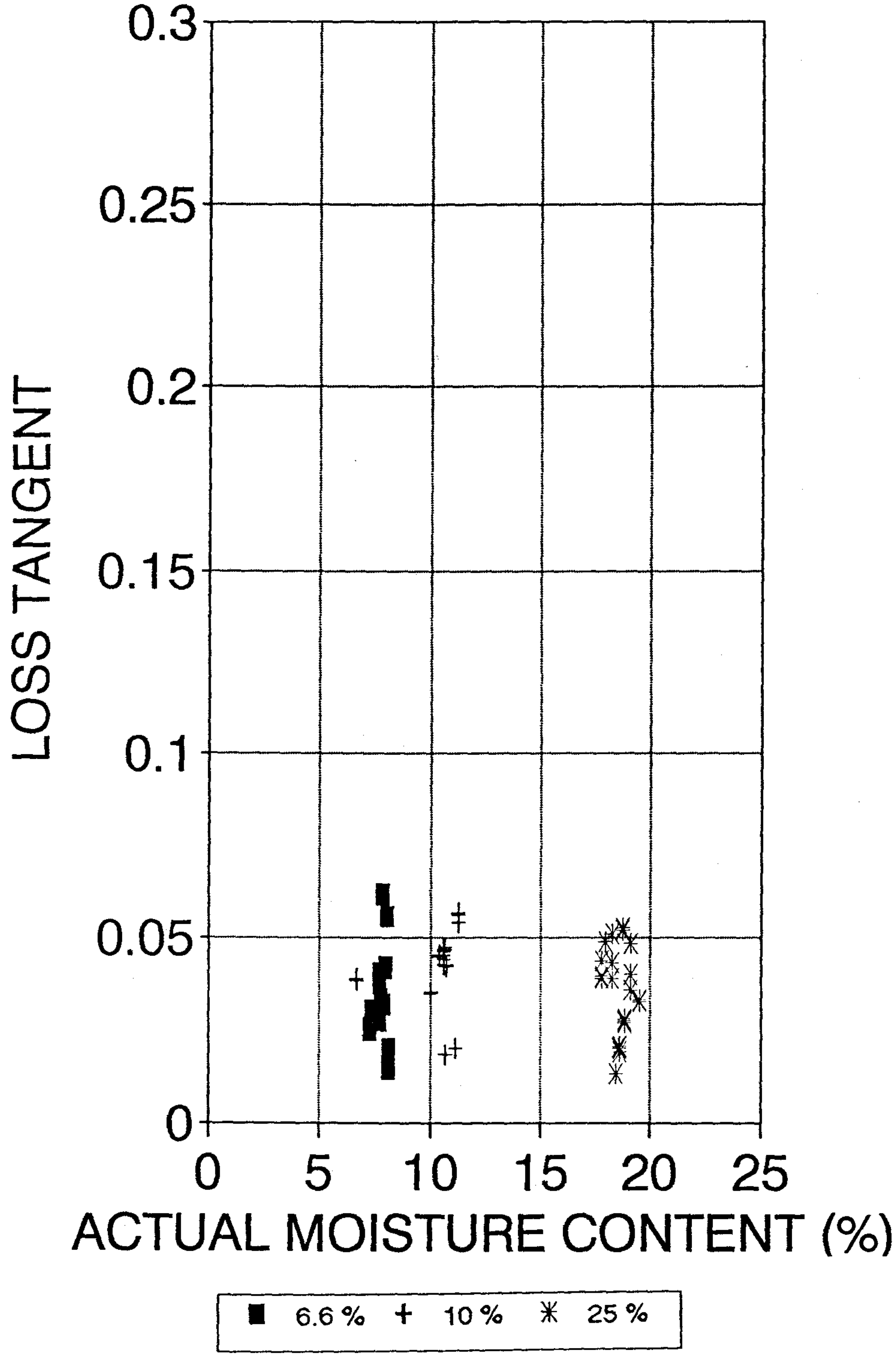

Figure A.4.88. The effect of moisture on the loss tangent of medium open holes at 20 10 MHz.

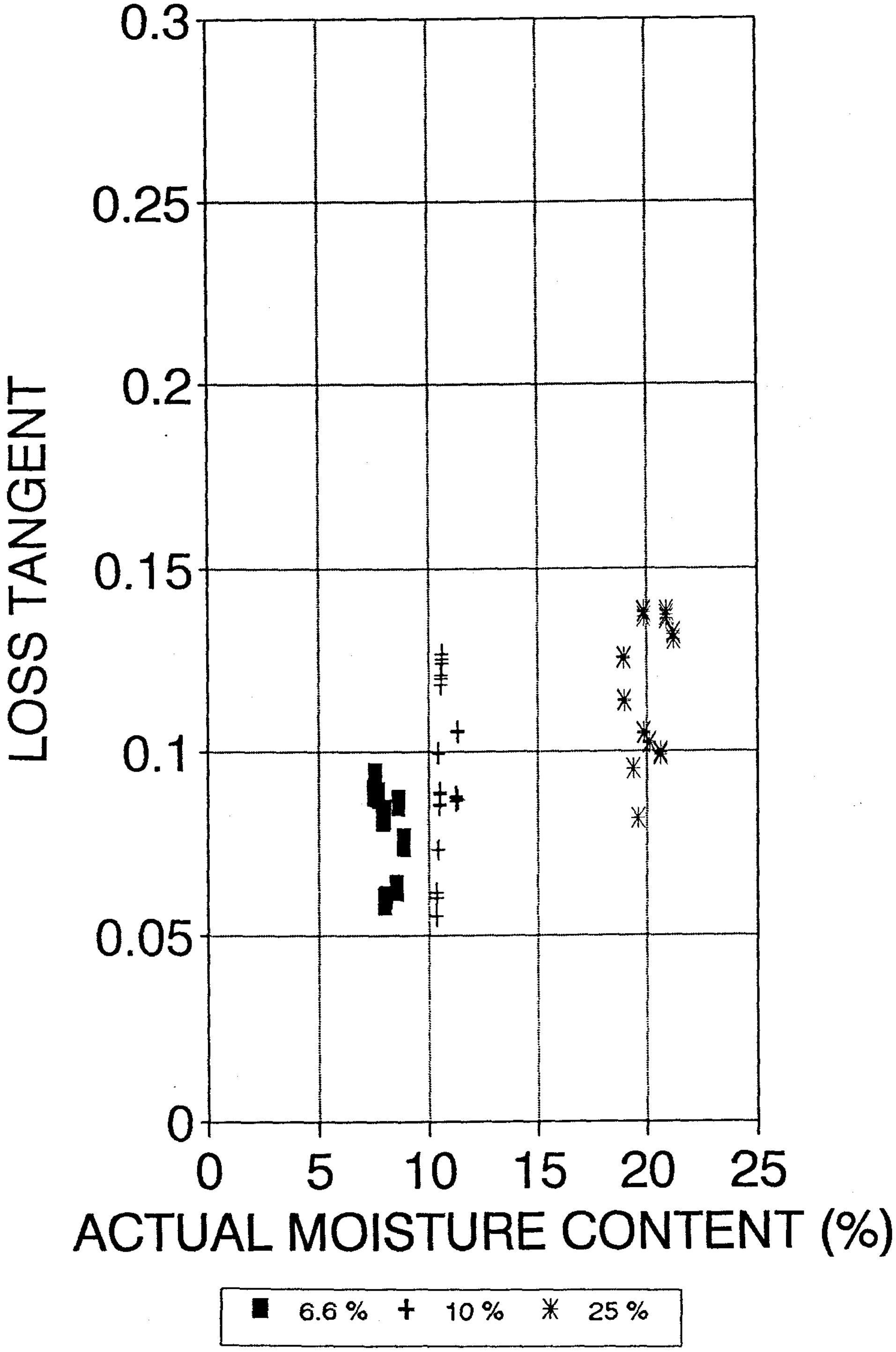

Figure A.4.89. The effect of moisture on the loss tangent of small open holes at 20 10 MHz.

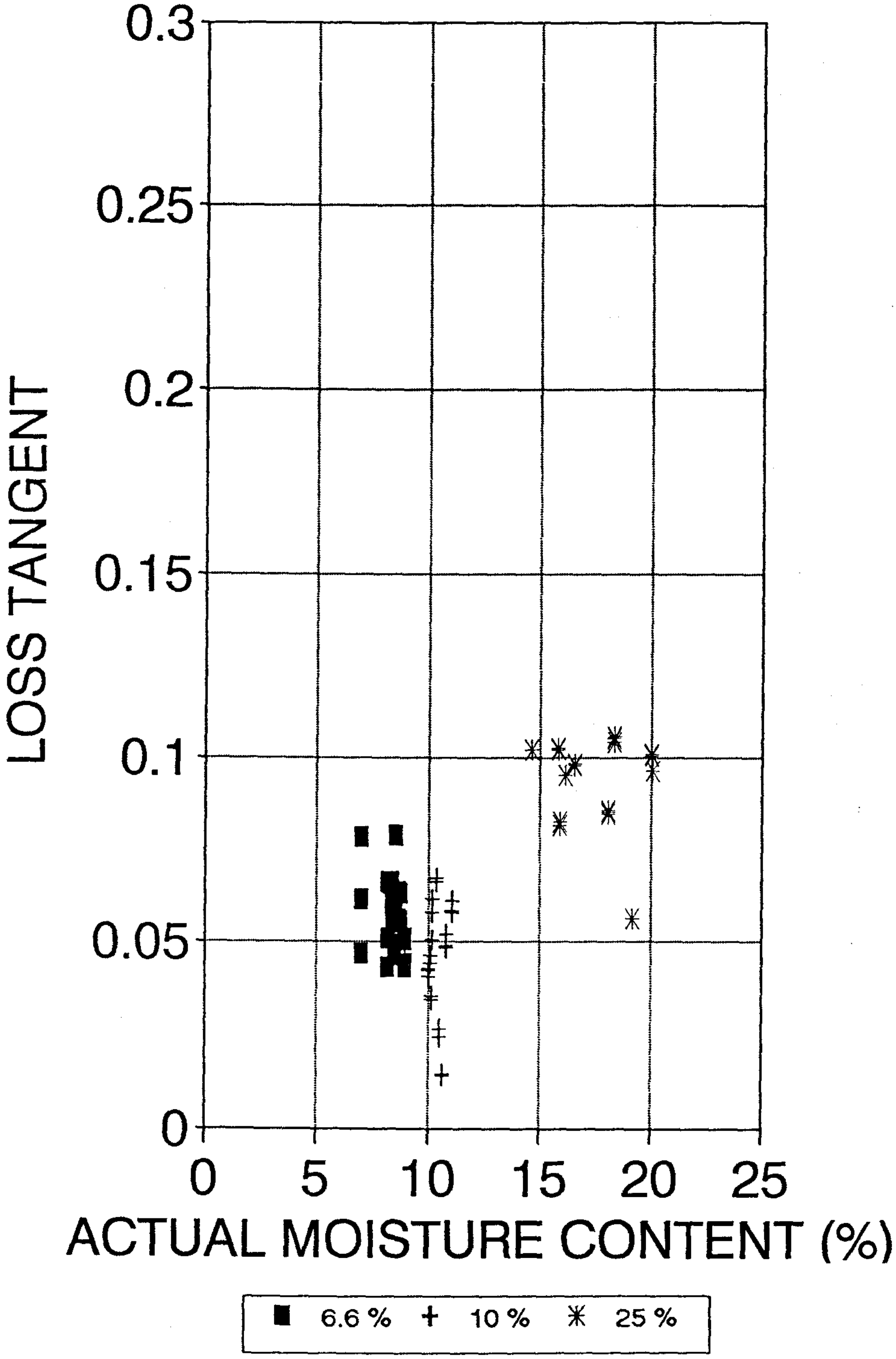

Figure A.4.90. The effect of moisture on the loss tangent of large pitch pockets at 20 10 MHz.

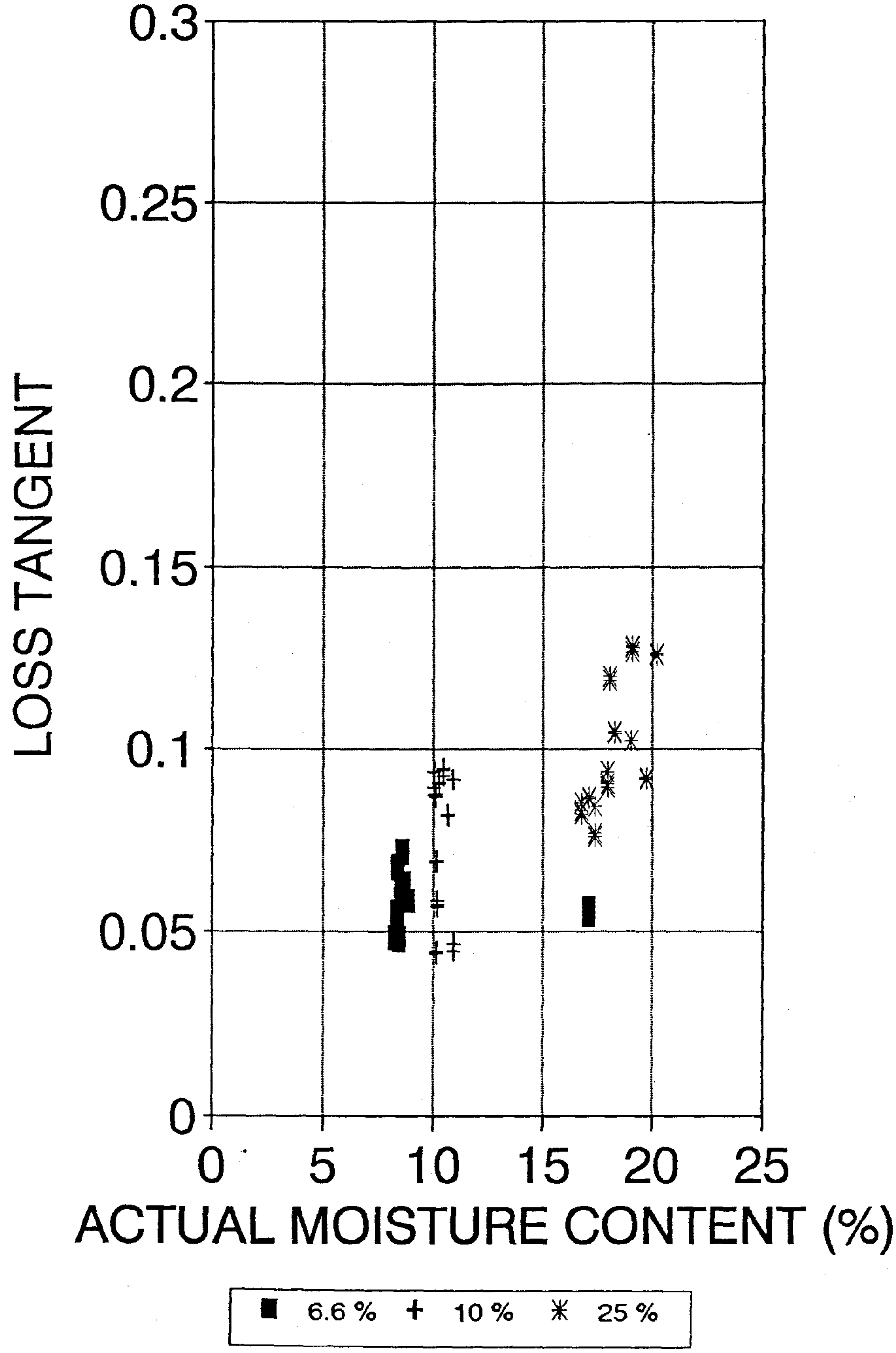

Figure A.4.91. The effect of moisture on the loss tangent of small pitch pockets at 20 MHz.

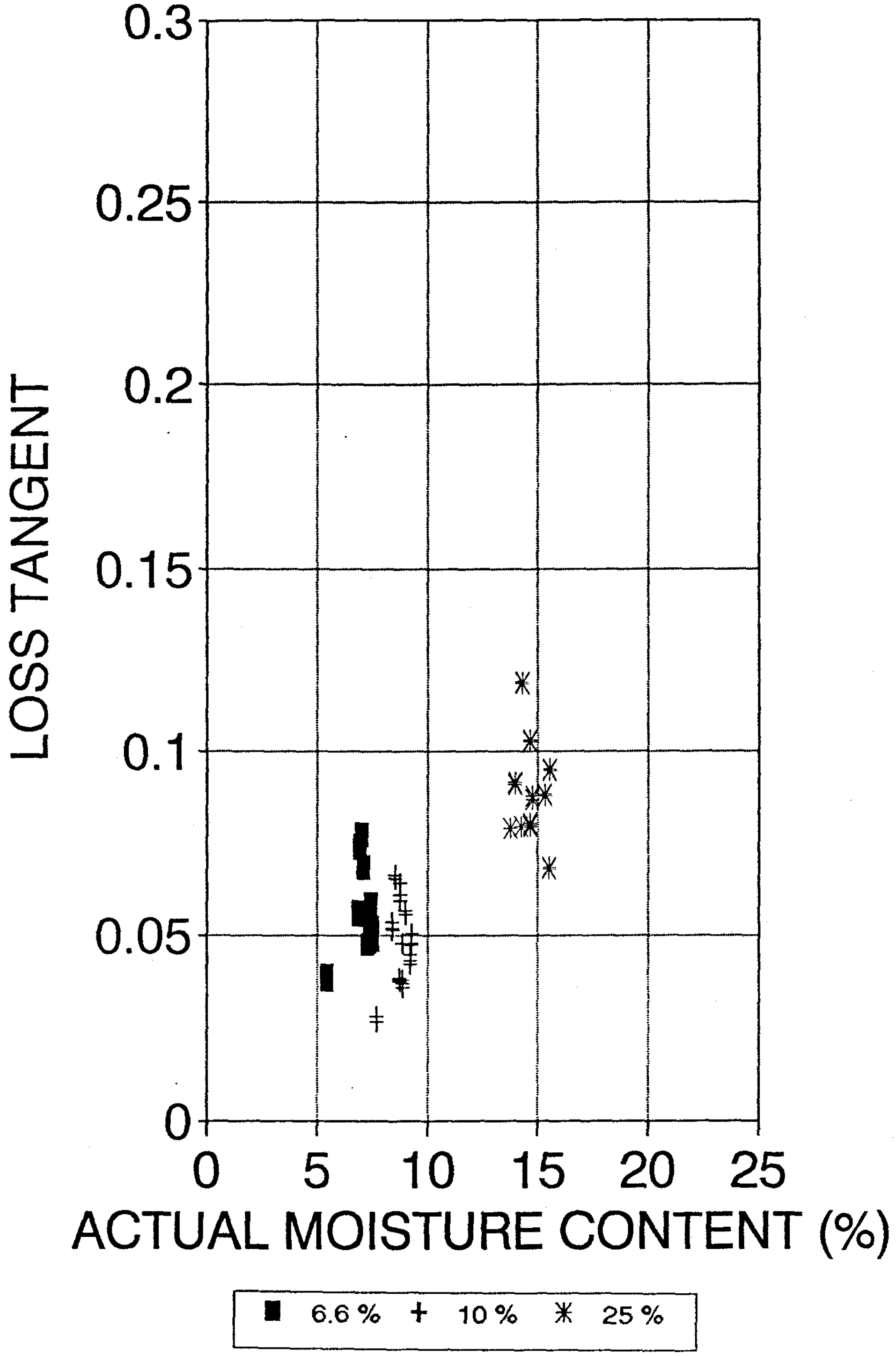

Figure A.4.92. The effect of moisture on the loss tangent of heavy pitch streaks at 20 MHz.

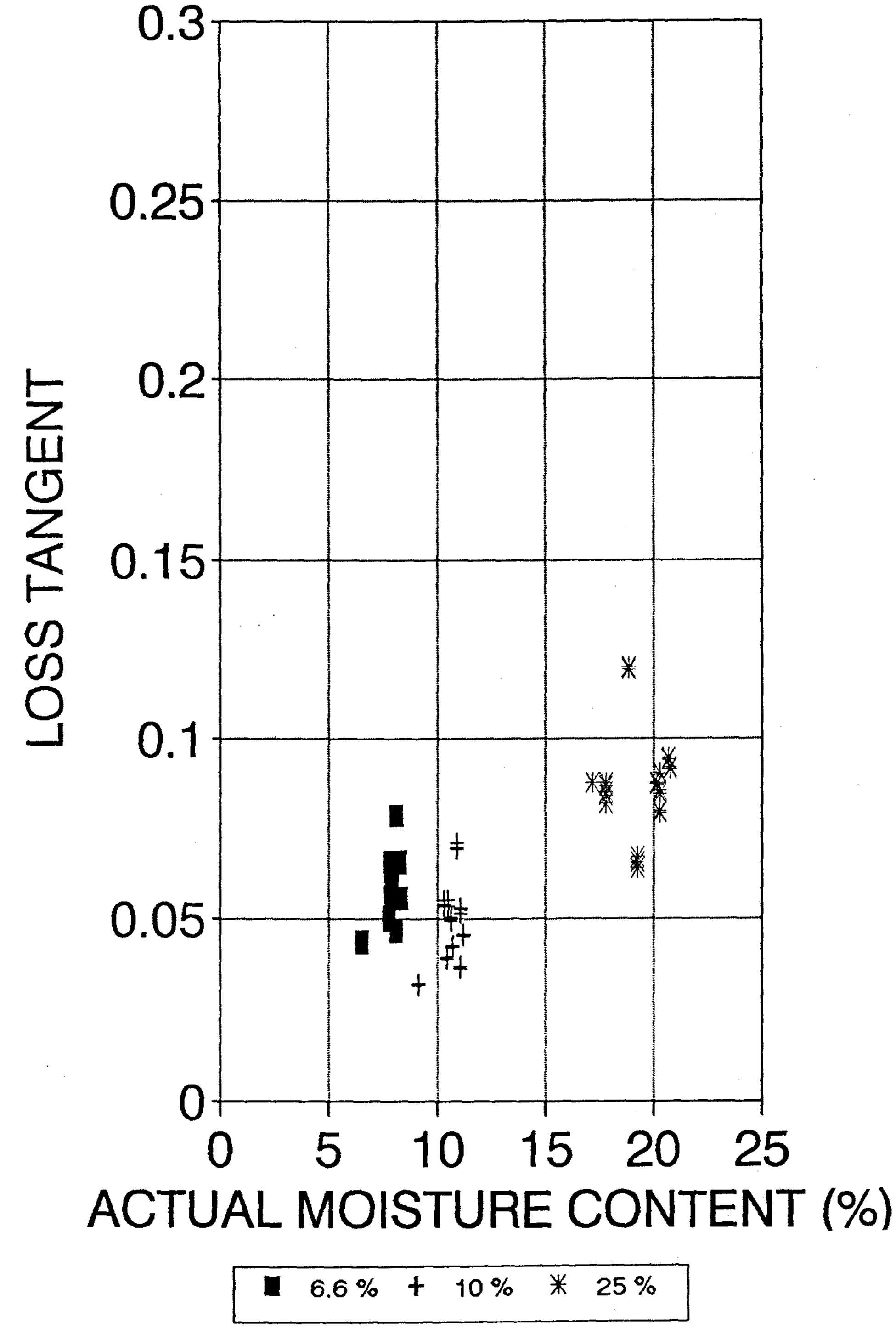

Figure A.4.93. The effect of moisture on the loss tangent of light pitch streaks at 20 MHz.

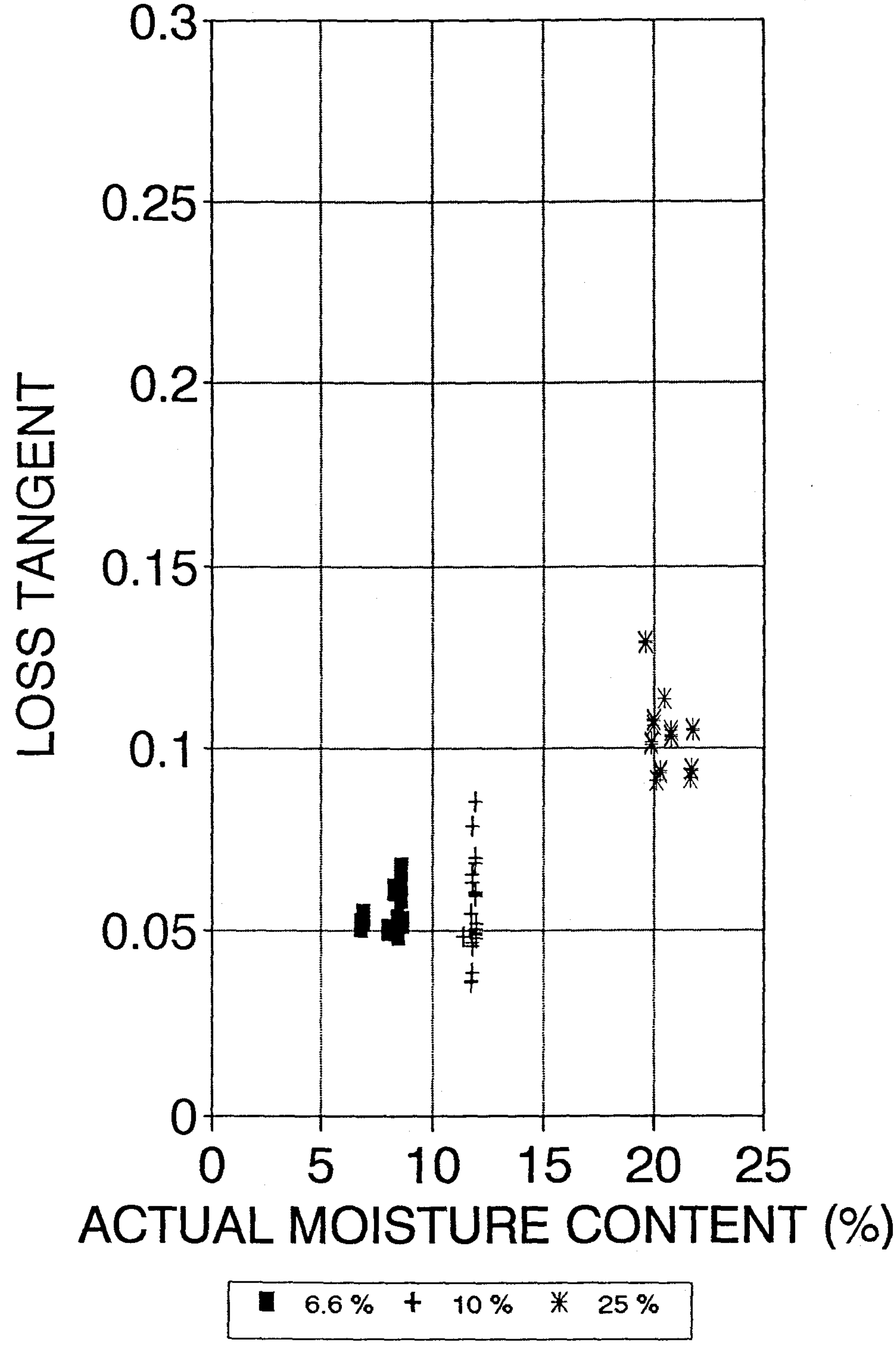

Figure A.4.94. The effect of moisture on the loss tangent of heavy blue stain at 20 MHz.

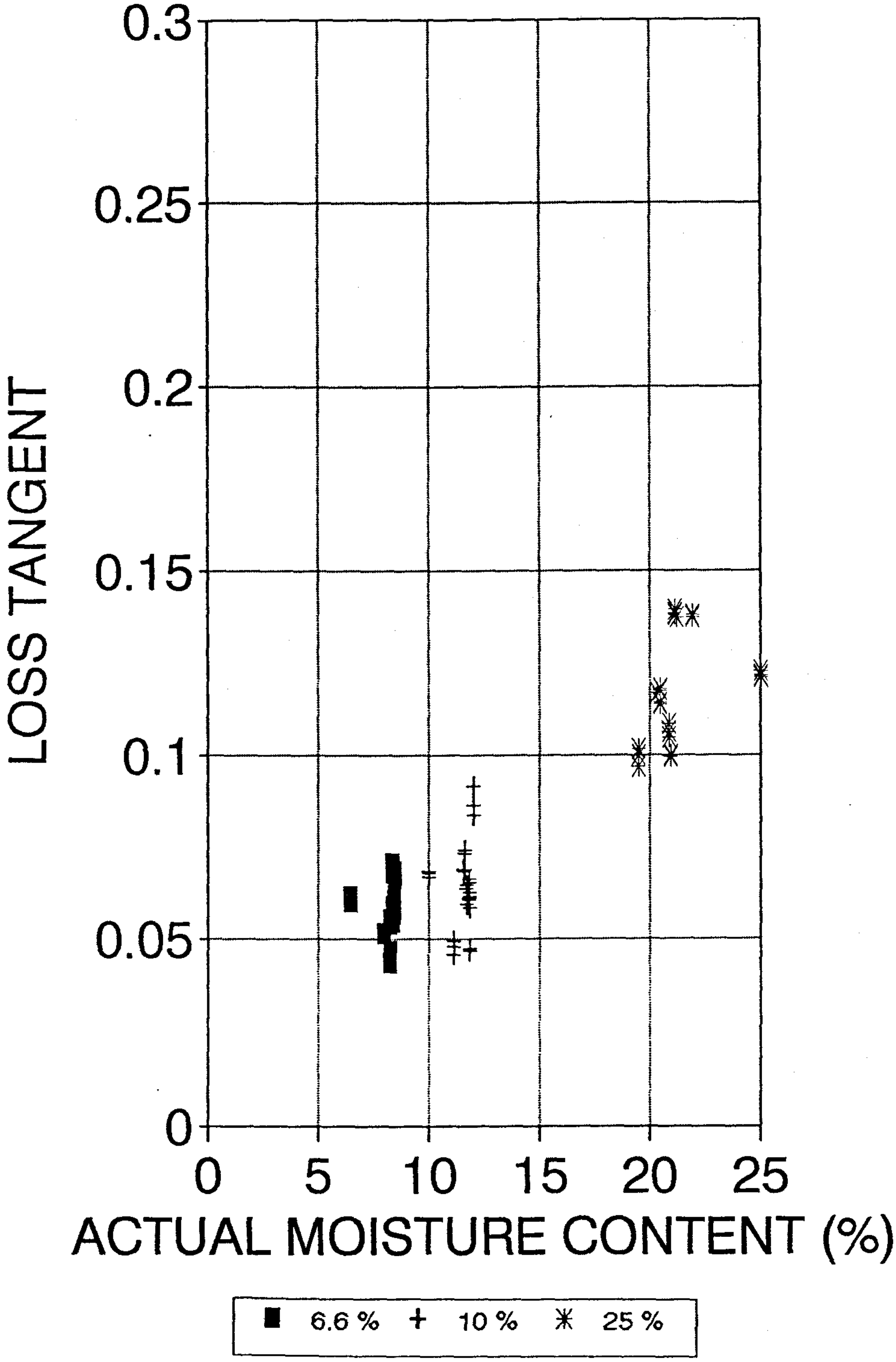

Figure A.4.95. The effect of moisture on the loss tangent of light blue stain at 20 MHz.

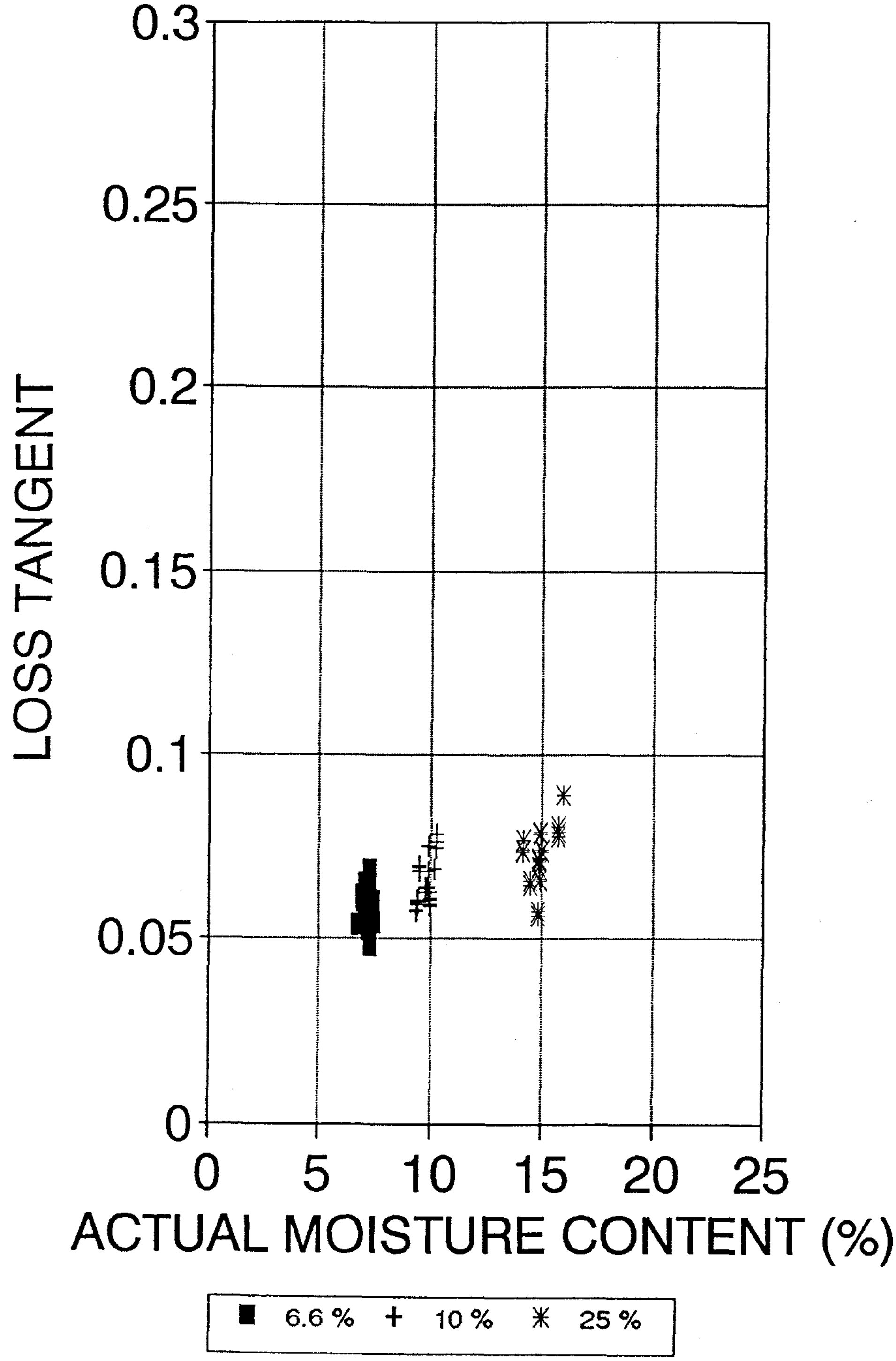

Figure A.4.96. The effect of moisture on the loss tangent of clearwood at 20 MHz.