

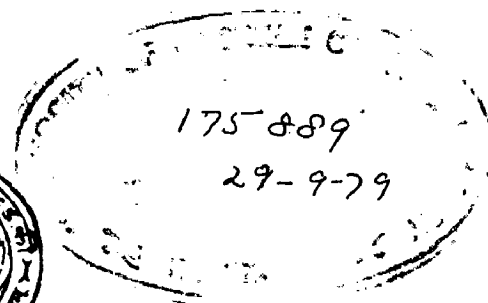
MEASUREMENT OF MOISTURE IN CONCRETE

A DISSERTATION

*Submitted in partial fulfilment
of the requirements for the award of the Degree
of
MASTER OF ENGINEERING
in
MEASUREMENT AND INSTRUMENTATION*

By

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DEPARTMENT OF ELECTRICAL ENGINEERING
UNIVERSITY OF ROORKEE
ROORKEE, (INDIA)
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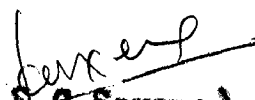
C E R T I F I C A T E

Certified that the dissertation entitled
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partial fulfillment for the award of the Degree of
Master of Engineering in Electrical Engineering
(Measurement and Instrumentation) of the University
of Roorkee, Roorkee is a record of student's own
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A C K N O W L E D G E M E N T

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(Gajendra Mohan Tayal)

A B S T R A C T

Concrete is essentially a natural stone which has very wide applications as a structural material. Water is one of the main constituents of concrete which reacts with cement to form a binding paste which, by penetrating into the minute surface irregularities of sand and coarse aggregate, brings them into close cohesion and therefore water has great influence upon the various properties of concrete. The present dissertation gives an account of the various properties of concrete and influence of water upon them. Several existing techniques and instrumentation developed for the measurement of water content in concrete have been critically reviewed in this dissertation. A compact and portable instrument for the measurement of moisture in concrete developed by the author has been described. This instrument, in which a capacitive transducer has been used as a sensor, can be used for the measurement of moisture continuously or intermittently.

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I INTRODUCTION

Stone has been man's natural building material for thousands of years either in its natural block form or crushed and recemented to suit the needs of its structure. Concrete is essentially a natural stone which has traversed a cycle from solid to crushed and back to solid by cementing it back to a solid mass. As a structural material, therefore, concrete has a much wider application than has been utilized hitherto. With increased research on its behaviour, improvement in technology of its preparation and imagination in the evolution of structural systems, the possibilities for its use are boundless.

Water is one of the main constituent of concrete. The basic function of water in concrete is to react with cement to form a binding paste which, by penetrating into the minute and multitudinous surface irregularities of sand and coarse aggregate, brings them into close adhesion. The water absorbed by the concrete is called as moisture in concrete. By suitably adjusting the proportions of water, cement and aggregate, it is possible to get concrete for various purposes, namely a tough mix for road work, a rich mix for columns and a lean mix for foundations. Water has great influence upon the various properties of concrete e.g., if the amount of water increases above that necessary for complete hydration of cement, it merely produces a more porous structure and results in a decrease in strength.

Therefore, several techniques and instrumentation for the measurement and control of moisture in concrete have been developed and are in use throughout the industry.

The work embodied in this dissertation is divided in five chapters. Chapter II deals with the various properties of concrete and the influence of water content upon them. A review of the existing methods which are used for moisture measurement in concrete is given in Chapter III.

Chapter IV deals with an instrument which has been developed for the measurement of moisture content in concrete. Capacitive transducer has been used as sensor. It is a simple, compact and portable instrument which can be used in the field. The instrument can be used for the measurement of moisture continuously or intermittently. It can also be used for knowing the moisture content at various points in big size concrete samples. The conclusions are given in Chapter V.

II CONCRETE, ITS PROPERTIES AND AFFECT OF WATER ON ITS VARIOUS PROPERTIES

2.1 CONCRETE¹

Concrete is a constructional material which consists essentially of a binding agent and a mineral filler. The binding agent is an hydraulic cement which develops its strength when mixed with water and, by hydration, changes from a loose powder to a hard, brittle, stone like material. When cement reacts with water, part of the water is chemically combined, but remainder dries out, causing the set cement to shrink. To overcome the disadvantage of this shrinkage and also to reduce the cost of the concrete (which is mainly due to cement) an inner filler is used. This usually consists of large, medium and small pieces of rock combined with sand. In properly mixed concrete the filler is coated with a layer of cement paste, and the reaction of the cement with the water combines the whole mass into concrete. The filler or aggregate as it is termed, forms about 75% by volume of the whole mass. By suitably adjusting the proportions of cement, aggregate and water, it is possible to get concrete for various purposes, namely a tough mix for road work, a rich mix for columns and a lean mix for foundations.

2.2 PROPERTIES OF CONCRETE^{2,3}

The following section deals with the important properties of the two types of concretes:

(1) Plastic concrete

(11) Hardened Concrete

2.2.1 Elastic Concrete

Elastic concrete is a freshly mixed concrete which can be cast into various shapes. On being allowed to stand it will set and take the shape of the mould and remain rigid. The relative amounts of cement, aggregates and water mixed together control the properties in the wet state as well as in the hardened state. The important properties in the plastic state are workability, resistance to segregation, bleeding and harshness or cohesiveness of the mix.

Workability

By workability is usually meant the ease with which concrete can be handled from the mixer to its final fully compacted position. This includes the facility with which it can be charged into and discharged from the conveying equipment, the ease with which it can be placed in the form work, and the amount of vibration necessary for full compaction. Knowledge of the workability is very necessary in the production of a "well designed" concrete mix. The best guide to judge workability is experience.

Segregation

This is the mechanical resorting of the concrete into its constituent parts. The large aggregate is separated

from the cement mortar and becomes devoid of fine material. Segregation is caused by bad handling and placing which breaks up the cohesion of the mass of concrete. Chutes, conveyor belts and other methods of discharging concrete into a coned heap cause segregation. Segregation can also be produced by over vibration, this causes the large aggregate to sink to the bottom and displace the fine mortar upwards, but such segregation usually takes place only with very wet mixes.

Bleeding

It is the separation from the wet concrete of water or water and cement, and may be associated with wet segregation. The solid particles of coarse and fine aggregate settle, with a consequent rise of the water or a water/cement mixture. This produces a weak surface which in the case of a road slab will disintegrate. Bleeding is usually due to too much water and a lack of fine material, and can be remedied by proportioning the mix to include more sand and if necessary by adding more cement. Bleeding may also take place by the escape of cement slurry between the joints of the formwork. This results in unsightly honey combing and can be remedied only by better construction of the form work.

2.2.2 Hardened Concrete

The properties of concrete in plastic state are important only in the construction stage, whereas the properties of concrete in the hardened state are important for

the remainder of its life. In practice, however, it is impossible to consider both sets of properties separately, as they affect each other. They are so intertwined that they always have to be considered together, and in attempting to attain one property a compromise has to be made in the other properties. For example, high strength concrete with low shrinkage can be achieved only by the use of a low ratio of water to cement and a high proportion of large aggregate. Such a mix will probably be harsh and unworkable in the plastic state. If it is to be placed in thin sections it needs to be workable and somewhat cohesive, and large aggregate cannot be used. The workability will have to be increased, the mix made richer in cement and the total water content increased, all of which will tend to increase the shrinkage.

The main properties of hardened concrete are strength, permeability, shrinkage, elasticity and creep. They all change with time and depend upon, or are affected by, the moisture content of the concrete. In building construction, strength, elasticity and creep are important; in water retaining structures, reduced shrinkage and high permeability are as important as strength; in a road slab, strength and resistance to deterioration are equally important. Thus it is impossible to say that one property is more important than another. However, as the strength of concrete increases, the other properties improve, so

strength is often considered as the most important property of concrete.

Strength of Concrete

The strength of concrete is its resistance to rupture, and may be measured in a number of ways. We have the strength in compression, in tension, in shear and in flexure. All these define strength by reference to a method of testing. Concrete is a brittle material with a compressive strength. When it fails under a compressive load the failure is essentially a mixture of crushing and shear failure. An approximation to the failure load can be made by assuming that the concrete, in resisting failure, generates both cohesion and internal friction. The strength of concrete for pavements and roads is often specified as a flexural strength while the compression strength is defined as the maximum load per unit area sustained by a concrete specimen before failure in compression.

Permeability

Concrete is a slightly porous material, in which water tightness and impermeability are often as important as strength. The permeability affect the life and value of concrete which is subjected to disintegrating agencies, and in hydraulic structures, low permeability is necessary to ensure watertightness. Permeability is that property

which permits the passage of water through the concrete when subjected to pressure. The cement paste is an impermeable material, but it is riddled by a mass of capillaries, often interconnected, so that the concrete is inherently permeable. The existing capillaries are formed during compaction, which causes the water to rise and so form channels.

Shrinkage

Concrete changes in volume with change in its water content; since most concrete tends to dry out after setting, this change usually results in shrinkage, but under certain conditions an increase in volume occurs. Shrinkage may take place while the concrete is still plastic due to conditions of rapid drying before setting, but more usually the shrinkage takes place due to slow changes in water content during the life of the concrete after it has set. Plastic shrinkage is the shrinkage which occurs before the concrete is set or has attained any significant strength. The principal cause of such shrinkage is the rapid evaporation of water from the concrete surface, and is most likely to occur in slab and pavement construction when subjected to hot sun. If fresh concrete is allowed to set and then dry it will shrink due to the changes which take place in the cement paste during hydration and drying concrete.

Creep

No material is completely rigid, and like other materials concrete distorts under the influence of applied forces. If, when the applied force is removed, the material completely recovers its original shape, then it is said to be perfectly elastic. Concrete is only partially elastic, since it suffers from creep during loading. For concrete, the relationship between strength and strain is not constant, but the strain increases with the length of time the concrete is under load. This non-linear deformation or creep occurs more quickly at first but at a decreasing rate during the loading period.

If concrete is loaded quickly, strain takes place, which as long as the load does not cause fracture or cracking, practically dis-appears when the load is removed so that the concrete returns very nearly to its original size. If, however, the load is maintained for some time and then removed the concrete does not return to its original size. It returns, almost to its original size over a period of time, but even after this period it will still be deformed. This permanent deformation is called permanent creep. The deformation which disappears gradually with time is known as recovery creep, or delayed elasticity, whilst the deformation which is recovered immediately the load is removed is the elastic deformation.

The strength of concrete has a considerable influence on creep. With-in a wide range creep is inversely proportional to the strength of concrete at the time of application of the load. This is indicated, for instance, in the data of Table I.

TABLE I

CREEP OF CONCRETE OF DIFFERENT STRENGTHS LOADED AT THE AGE OF 7 DAYS

Strength of Concrete lb/in ²	Creep 10 ⁻⁶ per lb/in ²	Product of creep & strength 10 ⁻⁵
2,000	1.40	2.8
4,000	0.80	3.2
6,000	0.55	3.3
8,000	0.40	3.2

2.3 AFFECT OF WATER ON VARIOUS PROPERTIES OF CONCRETE^{2,3}

Water is one of the main constituents of concrete. It has various functions; it reacts with the cement powder, so causing it to set and harden, and it is a lubricating liquid which enables the concrete to be placed as a semi-fluid and so facilitates its compaction. Water has great influence upon the following properties of concrete:-

- (i) Workability
- (ii) Strength of Concrete
- (iii) Shrinkage of Concrete
- (iv) Creep
- (v) Permeability

Workability

For any one value of the water/cement ratio there is one proportion of sand to coarse aggregate that produces the greatest workability, but this can often be determined only by experiments. A quantity of water about 25 percent of the weight of cement reacts with the cement, but more water than this is required to facilitate the ease of working and compacting. The ratio of water to cement usually varies between 0.35 and 1.0 depending upon the richness i.e. aggregate/cement ratio, the required strength of concrete and the workability.

Strength of Concrete

Among the various factors which influences the strength of concrete, the effect of water is of great importance. The strength is largely determined by the ratio of water to cement; the higher the water/cement ratio, the lower the strength. As the amount of water increases above that necessary for complete hydration of the cement (Water/Cement ratio of about 0.22 to 0.25) it merely produces a more porous structure and results in a decrease in strength. Concrete with a water/Cement ratio of 0.25 cannot

be made, because it cannot be fully compacted. The relation between strength and water/cement ratio for ordinary Portland cement is shown in Fig.2.1.

There is not just a single relation but a number of relations. For example, as the mix becomes wet and very workable, the strength falls off from that which would be predicted from Fig.2.1. Similarly, as the mix becomes too dry it becomes impossible to compact fully, and again the strength is less than would be expected. In fresh concrete, the aggregates contain water; if the aggregates are dry when placed in a mixer, they absorb water and leave less available for mixing with the cement, if the aggregates are saturated and contain water in the interstices, this will make the mix wetter. Between these two conditions there exists one in which the aggregates neither detract from nor add to the water added for mixing with the cement. This is when the aggregates are saturated inside but dry on the surface. As far as strength is concerned, the effective water/cement ratio is the ratio of the amount of water, added to a mix when the aggregates are saturated surface dry, to the amount of cement.

The strength is affected not only by the water/cement ratio, but also by the total quantity of water used per unit volume, so that if the water/cement ratio is maintained constant but the mix proportions varied so that less water

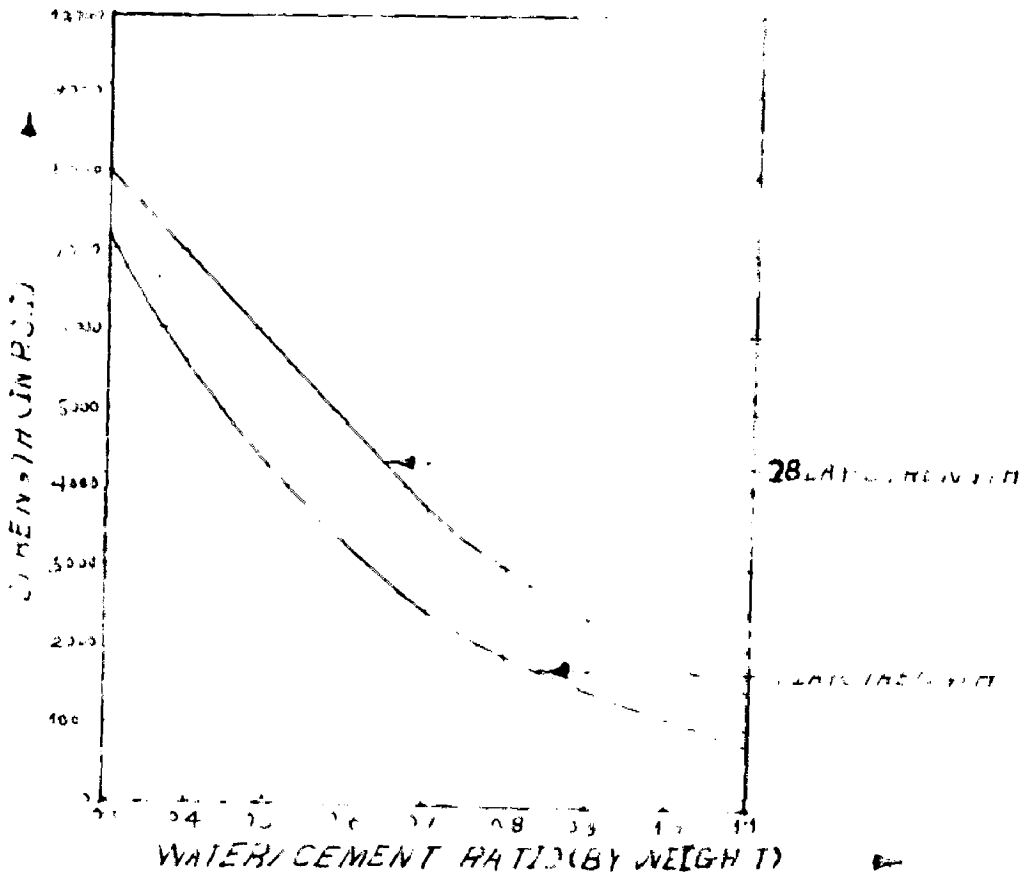


FIG-2-1 RELATIONSHIP OF STRENGTH AND WATER/CEMENT RATIO FOR ORDINARY PORTLAND CEMENT

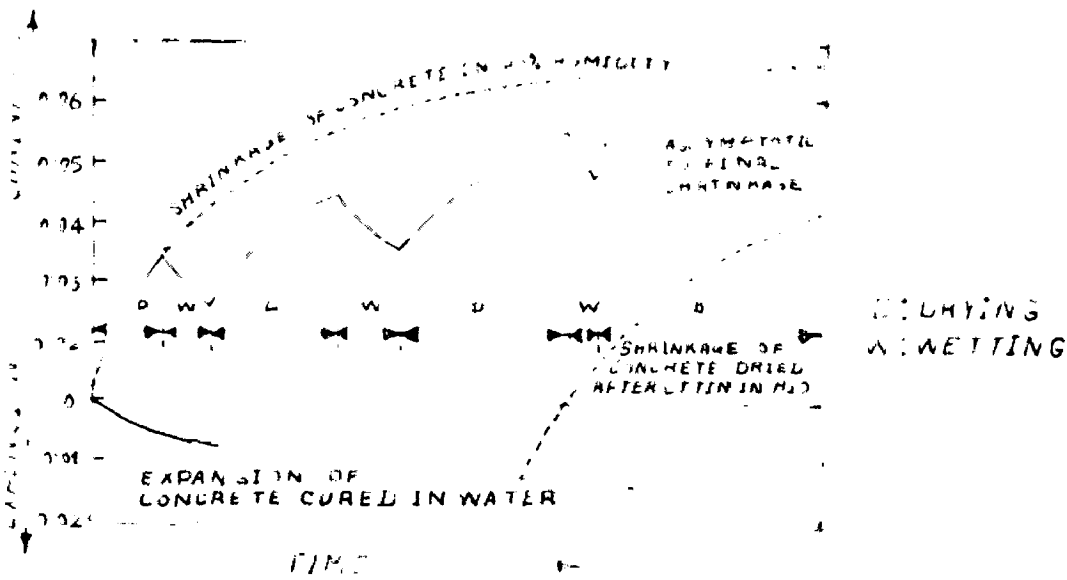


FIG-2-2 EFFECT OF RELATIVE HUMIDITY ON SHRINKAGE OF CONCRETE

is required per cubic meter of mix, then that mix will be stronger.

Shrinkage of Concrete

The shrinkage of concrete, or rather its volume, change due to the effect of moisture, is caused by the chemical combination of the cement with water and the changes in moisture content of the concrete mass. The hydration of the cement produces a gel which binds the particles of aggregates together. As hydration occurs part of the water is absorbed by the gel and this causes some contraction of the total volume of cement plus water. Where the concrete can dry out, water flows from the gel through the minute pores and capillary channels, and there is a reduction in the volume of the cement gel and a total decrease (or shrinkage) in the absolute volume of the solids. Most of this is reversible, so that on subsequent thorough saturation the concrete regains much of the shrinkage. Concrete cured under water does not shrink- on the contrary, it expands slightly (Fig.2.2).

Shrinkage varies directly with the water/cement ratio, the higher the water/cement ratio the greater being the shrinkage. For concretes with equal water/cement ratios, that containing more water per cubic meter shrinks more (Fig.2.3).

In general, concretes with low water/cement ratios are usually rich mixes (i.e. with low aggregate/cement ratios) but the amount of water they contain per cubic

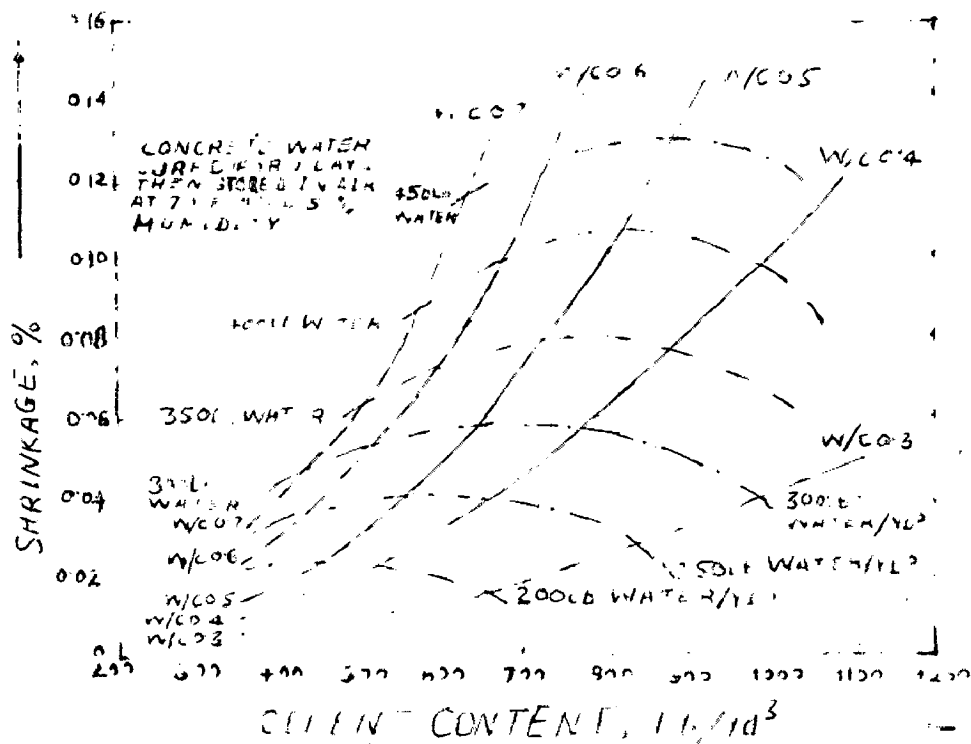


FIG. 2.5 SHRINKAGE-THE EFFECT OF WATER AND CEMENT AND WATER/CEMENT RATIO.

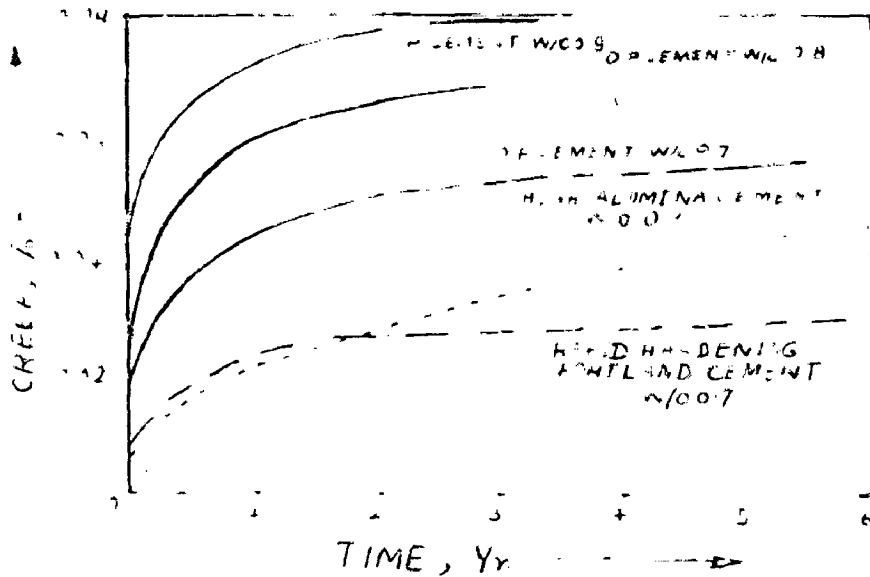


FIG. 2.4 CREEP-THE EFFECT OF CEMENT AND WATER CONTENT

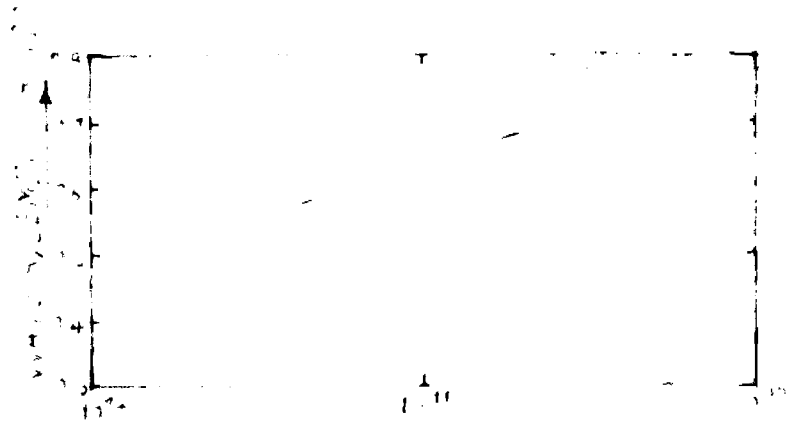
meter of concrete is high, because the cement content is high. In such cases the lower shrinkage resulting from a low water/cement ratio is over balanced by the greater shrinkage due to the rich mix and the high total water content, so that rich mixes with low water/cement ratios may shrink more than a lean mix with a higher water/cement ratio.

Creep

Creep increases with increasing water/cement ratio. Creep is less for high aggregate/cement ratios and it increases with increasing richness of the mix, but the effect is masked largely by the over-riding effect of the water/cement ratio which results in creep being greatest with lean or weak mixes when the water/cement ratio is high in order to achieve a workable concrete (Fig.2.4).

Permeability

The effect of water/cement ratio is to reduce the permeability. The permeability increases as the voids ratio increases, but if the water/cement ratio is too low for complete compaction the effect of the low water/cement ratio in reducing permeability will be more than offset by incomplete compaction. The water content per cubic meter of concrete also affects the permeability, which increases with an increase in water. The water content is affected



max Moment at $x = 1.5$ and $y = 4$

at $x = 1.5$ and $y = 4$ the moment is $M = 1.5 \times 4 = 6$ units

by both the richness and the water/cement ratio, and for minimum permeability it is essential to adjust the richness and water/cement ratio so that the water content is a minimum consistent with adequate workability.

Fig.2.5 shows the affect^{of} water/cement ratio on permeability.

III METHODS OF MOISTURE MEASUREMENT

The methods of measurement of moisture content can be broadly classified into two groups i.e. direct (Chemical) methods and indirect (Physical) methods. In the direct method moisture is normally extracted from the material by oven drying, desiccation, distillation and other chemical techniques, and its quantity found by weighing or by observing the pressure or temperature changes of the chemical reaction. Techniques based on these principles are usually employed in the laboratory and are found to be accurate and in most of the cases (with proper precautions in sampling) absolute values can be obtained. In the indirect method, the moisture content is not extracted from the material, instead parameters of the wet solid dependent on the quantity of water present are measured. These take several forms, depending upon the property of water used, and a variety of instruments have been devised. The readings obtained are purely arbitrary and they have to be calibrated against moisture values found by one or more of the direct methods. These two methods have their own advantages and disadvantages. It is possible to get very accurate and even absolute values by employing one or more of the direct methods. The time taken in these methods, however is usually considerable and operations are mostly manual. Indirect methods, though dependent in accuracy on the results of direct measurements against which they are calibrated, offer the quickest mode of moisture deter-

mination. Only the indirect methods offer the possibility of continuous measurement and automatic control of moisture content in industrial processes. Once a particular instrument has been calibrated at a certain setting, very little attention and time are required to measure or control the moisture content of the material. The increase in instrumentation has been one of the striking advances made in chemical technology over the past decade or so, and today the determination of moisture is more often achieved by instrumental methods rather than by direct chemical analysis.

The development of instrument technology for the measurement of the moisture content of the materials has undergone a radical change in recent years and there has been a revolution of methods and results these days in estimating moisture content of samples by the application of modern physical techniques such as electronics, infra-red spectroscopy, nuclear magnetic resonance spectroscopy (NMR), neutron-scattering etc. These techniques have been developed based on some unique physical properties of water or that of hydrogen (proton) which forms its main constituent.

3.1 ELECTRICAL OR ELECTRONIC METHODS OF MOISTURE MEASUREMENT^{4.5}

Water shows two important electrical properties, i.e. conductivity and dielectric. In scientific investigations and technological developments of electrical or

electronic instruments these two fundamental properties have been utilized, and, therefore first a short description of these properties is presented here before giving details of electrical or electronic devices and equipments.

3.1.1 Resistive Type Moisture Measuring Instruments Conductivity of Water⁴

Water is a dipolar as well as a typical associated liquid. A water molecule can be considered as composed of a negative ion (O) with two positive ions (H). When an electric voltage (below break down strength) is applied it shows conduction due to the presence of (H) and (OH) ions. Even the purest water conducts to a certain extent. Kohlrausch and Hey-Weiller obtained very pure water whose conductivity was only $4.3 \times 10^{-8} \text{ Ohm}^{-1} \text{ cm}^{-1}$. Using temp. correction, this value was reduced to $3.84 \times 10^{-8} \text{ Ohm}^{-1} \text{ cm}^{-1}$ at 18°C . This value exceeds by 10% the theoretical conductivity data computed from equivalent conductances of (H) and (OH) ions and ion product of water. In contact with air, water dissolves carbon dioxide and the conductivity rises at 25°C to about $8 \times 10^{-7} \text{ Ohm}^{-1} \text{ cm}^{-1}$. It is a well known fact that dissolution in water of substances identified as electrolytes causes an increase in electrical conductivity, and therefore the water usually met with in laboratories and industrial testing has a higher

conductivity. Ordinary distilled water was found to have a conductivity of $2.18 \times 10^{-6} \text{ Ohm}^{-1} \text{ cm}^{-1}$ as measured by a Phillips conductivity Bridge.

However, for the development of electrical method of moisture measurement, resistance (reciprocal of conductance) is more important as in most of the electrical instruments developed, the relationship between two fixed points and moisture content has been used. The electrical resistance of a material is usually expressed as its specific resistance which is defined as the resistance between the opposite faces of a one cm cube of the material. For many of the materials to be encountered in connection with measurement of moisture by electrical methods, linear density of the specimen can be more easily defined and measured. In some cases it is more convenient to use the mass specific resistance which is defined as the resistance of a uniform specimen of mass of one gram and one cm length. The units of mass specific resistance are Ohm-g/cm^2 .

The specific resistance of water below its boiling point increases with increase in temp. and hence measurement of moisture content using this specific resistance property of water should be made at a fixed temp. (if possible) or necessary temperature corrections should be applied.

^{of}
Theory D.C. Conductivity Or Resistance Type
Moisture Meter

It has been observed by a Number of investigators that there is a definite relationship between the moisture content of hygroscopic materials and their d.c. conductivity or d.c. resistance. Kujirai and Akshari studied the resistance variation with changing humidity conditions and found that resistance fell with increasing humidity, the logarithm of the resistance being practically a linear function of the humidity. They also studied the affect of the duration of application of the voltage and found that, at medium and high humidities, resistance rise was gradual and it continued to rise for five minutes after the current was switched on, whereas if the relative humidity was below 30%, the resistance was not dependent on the time factor. Murphy and Walker obtained similar results. They showed that the log of resistance varied linearly with moisture content. At a given moisture content, the ordinary resistance law governing solid conductors, i.e. $R = \ell/A$, appears to hold approximately correct for many hygroscopic materials, where R , ℓ and A are resistance, length and area of conductor respectively. Such factors as density, direction of current flow relative to grain structure, variation of the specimen beyond the electrodes and similar geometrical factors are relatively unimportant

compared to the large change of resistance with respect to change of moisture. The relation between logarithm of specific resistance and moisture content is approximately straight lines for different woods and textiles materials and soils.

According to Kawasaki, when the moisture content is low, the conduction current is given by the following relationship

$$\log \frac{i}{i_0} = \alpha M \quad \dots \quad (3.1)$$

Where i and i_0 are the intensities of currents through the sample sorbed and desorbed respectively, M the moisture content and α a constant. However if the moisture content is high, the conduction current does not follow the above equation and the following equation then holds:

$$i/i_0 = 1 + \beta M \quad \dots \quad (3.2)$$

where β is another constant.

The conduction current increases linearly with moisture content upto a certain critical point depending upon the material.

Besides the moisture content, the conductivity or resistance of a hygroscopic material is also affected by the presence of naturally occurring electrolytes in the material. The local changes may seriously effect the conductance if the measuring current is passed for longer

time. It is, therefore, essential that the measurements are made as quickly as possible. This is of great importance due to the fact that AC and DC conductivities are of the same order only when DC measurements are made with in a period of electrification short enough to avoid the error due to polarisation.

Sinjelnikoff and Walther have shown that the true dc conductivity of a dielectric is equal to its ac conductivity. The apparent discrepancy between them is due to an error in the dc measurements caused by a back emf. of polarisation which makes the apparent resistance much larger than the true resistance. However it has been shown by Murphy and Walker that there is wide discrepancy between the ac and dc conductivities of cotton at humidities below 80% though at humidities higher than this the two conductivities are equal.

Description of Conductivity or Resistance Type Moisture Meters

Based on the principle of dc resistance variation described earlier, a large number of conductivity or resistance type moisture meters have been developed. All these instruments have three basic units:

- (i) The Electrode System
- (ii) The Electronic Unit
- (iii) The indicating Meter or Recorder.

For measurements, the sample is held between the two prongs of the electrode and the current flowing through the sample is measured by the electronic unit and indicated on the meter directly as moisture content.

(i) The Electrode System

The electrode system varies with the type of sample to be examined. For resistance measurements the electrode should always have two points (separated by a fixed distance having proper insulation) between which the sample can be grabbed. ^{For} large number of wood products, soils, clays, sands etc. the electrode system generally consists of about half a dozen sharp points or tapering needles embedded in suitable insulation and mounted on a handle so that these needles may be driven directly into the sample to a depth of 1/4" or so. These needle points are generally fixed from each other about 1" apart (Fig.3.1.) For grains, coal, food-stuffs and chemicals in powder form and other granular materials, the electrode system usually consists of two insulated hollow cylinders forming annular space for holding these materials. Provision is made to apply a known pressure by means of a spring type of electrode system which has been developed by Jones and the hydraulic type made by Reddick. It has been found by Jones that by compressing the samples within the field of measurement by applying a force normal to the force

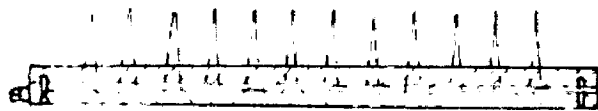


FIG. 31. VARIATION OF NEEDLE TYPE ELECTRODE

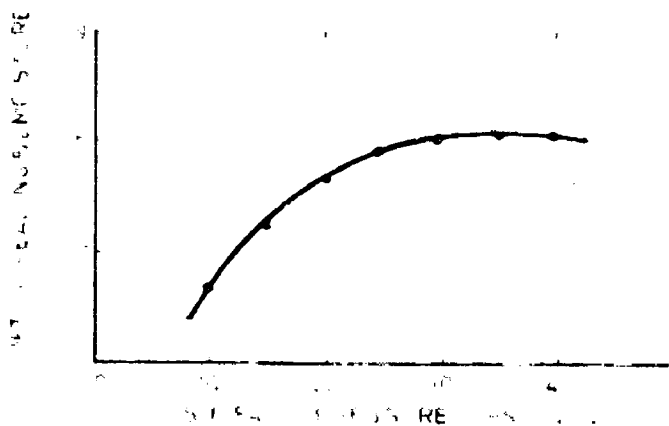


FIG. 32. VARIATION OF RELATIVE HUMIDITY WITH APPLIED PRESSURE

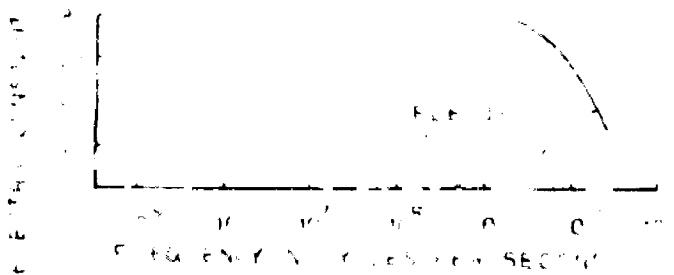


FIG. 33. SHOWING RELAXATION SPECTRUM OF WATER VARIATION ^{OF} ELECTRIC CONSTANT OF WATER WITH CHANGE IN FREQUENCY

of the electrodes until a certain state of compression is reached, the measured resistance of the sample becomes practically independent of the initial state of packing and is not appreciably altered by any further increase in the force applied to the electrodes. A minimum force of about 20 Kg. was found adequate to produce the required state of compression. A graph showing variation of moisture content with applied surface pressure is shown in Fig. 3.2.

(ii) Electronic Circuits

Some of these instruments employ a basic Wheatstone Bridge circuit for measuring the high resistances involved, which are of the order of thousands of Mega Ohms or hundreds of millions of Ohms at low moisture content and thousands of Ohms at high moisture values. For a moisture variation of 5% to 15% the resistance change is 1000 Megohms to 0.17 Megohms. The bridge detector is usually a sensitive, high impedance electronic voltmeter or galvanometer as it is required to measure extremely high values of resistance or very low conductances at low moisture contents and comparatively low resistances and high conductivities at high moisture. It has been found that the value of resistance depends on the following factors:

- (A) The moisture content of the sample;
- (B) Type of material
- (C) Nature of the electrodes, i.e., the distance between the points between which the resistance is to be

measured.

However, the main contribution to the increase or decrease of resistance is by the variation of moisture content.

Some investigators and manufacturers have utilized the variation of anode current of a triode valve with change in grid bias by using the resistance offered by the sample containing moisture as a part of the grid bias resistor. It is well known that for a certain range of the grid bias, the anode current of a triode varies linearly (for a limited range) with change in grid bias if the anode voltage is kept constant. Also, from the principle of voltage measurement across a high resistance it follows that the measuring device should have a high internal resistance and this condition is satisfied in a suitable electronic valve which has high resistance between grid and filament. These principles have been used by Jones in developing the Shirley Moisture Meter.

Instead of a valve a transistor can be used which has several advantages. The development of this circuit is based on the principle of variation of collector current of a transistor in accordance with change in the voltage of the emitter.

(111) Indicating Meter or Recorder

After the relationship between the moisture content

of the sample and the emitter current of the transistor is obtained, it is required to get a direct relation between the current variation and the value of the moisture content. This can be obtained by the prior calibration of the meter scale by known values of moisture contents. Once the calibrated scale is substituted for the current scale, the values of moisture contents can be obtained directly in terms of percentage of moisture content for unknown samples. Instead of a current meter, a pen recorder can be used by which a continuous record of the variation of moisture content can be made in a processing operation.

Operating Considerations of Resistance Type Moisture Meter

For getting optimum operating conditions from the conductivity moisture meters the following factors should be taken into consideration:

(1) Moisture Distribution

Distribution of moisture throughout the sample should be very uniform. As the conductivity meters measure the path of least resistance, a single wet spot in the sample can vitiate the result enormously. In using needle type electrodes which contact only one side of the sample, surface moisture on the material should be avoided.

(ii) Range of Measurement

As the relationship between electrical resistance and moisture content is strictly speaking only true within the hygroscopic range of the material (usually 50% to 90% RH), some error is likely to be introduced in attempting to measure very low or very high moisture contents.

(iii) Temperature

Most meters are calibrated for samples having a temperature of 20°C to 25°C. If the sample temperature is higher or lower the meter readings should be corrected by applying the temperature coefficient correction which is about one percent for a temperature difference of 5°C.

(iv) Sampling

It is fundamental to any testing procedure that the larger the sample, the more representative is the result. The sample should be as nearly representative of the average of the material condition as possible. Two or three tests should be made to obtain the average of the uncontrolled variables.

(v) Packing Density

The sample should be kept under uniform pressure or compression to minimize errors due to lack of variation of conductivity as a result of variation in packing density. The same constant and uniform pressure should be applied to get repeatable and dependable results.

(vi) Purity of the Sample

Percentage of small amount of impurities in the sample in the form of an electrolyte, a salt or an acid will drastically affect the conductivity of the sample as a whole and will introduce error in the original calibration.

(vii) Method of Measurement

Moisture content of grab samples must be measured as rapidly as possible. However, due regard should be paid to the standardisation and balancing of the instrument before taking observations.

For hygroscopic materials, there ^{is} a possibility of error in meter readings due to dc polarisation effect. This can be largely minimised by using large electrodes. Also, to eliminate completely the errors due to polarisation effect, electrodes of stainless steel can be used.

Merits and Demerits of Conductivity Moisture Meter

(i) There is a considerable change in the resistance or conductivity for a comparatively small change in moisture regain. There is for many materials an almost linear relationship between the regain and logarithm of the resistance over the hygroscopic range, hence accurate results of moisture measurement can be made.

(ii) If the material is a natural product, resistance regain relationship is very minutely affected by the origin of the material or method of production if it is a manufactured material.

(iii) The moisture measurement is instantaneous after the sample is presented to the electrodes. Hence continuous measurement & control of moisture can be made in a processing condition.

(iv) Resistance is a property which can be measured by simple, robust and reliable apparatus and is most suited for certain types of materials.

(v) The moisture measurements are affected by the degree and efficiency of the contact of the electrodes with the samples. It is not always possible or practicable to obtain uniform standard contact (due to unevenness of the surface of the sample) and accuracy of measurement is of doubtful nature in such cases.

(vi) The conductivity is also very much affected by the presence of electrolytes, salts and acids, etc. and it is not possible to control these as the moisture content may vary with the quality of water used in processing the material. This a serious drawback of this type of meter.

3.1.2. Capacitive Type Moisture Measuring Instruments:

Dielectric Properties of Water and Its Variation with Temperature and Frequency

Water is an important dipolar dielectric and has a permanent dipole moment on account of its structure (H-O-H). The dipole moment of water molecule is a vector directed along the axis dividing this OH bond angle into two equal parts. Kirkwood has successfully calculated the dielectric constant of dipolar solids and liquids as well as its variation with temperature and, therefore the dielectric constant of water and its variation with temperature can be derived theoretically by Kirkwood's equation.

The following approximately relationship between static dielectric constant (ϵ_0) of water and temperature of water is obtained

$$\epsilon_0 \approx \frac{19,000}{T} \dots \quad (5.9)$$

This $\frac{1}{T}$ law has been verified experimentally and experimental results are found to be in fairly good agreement with Kirkwood's theoretical deductions.

There is no satisfactory theoretical treatment of the frequency dependence of the dielectric properties of water as such. Experimentally it has been observed that dielectric constant of water remains constant at 81 upto

1,000 Mc/s. Experimental determinations of dielectric constant of water at different frequencies have been made by Saxton and Lons as well as colleve, Hasted and Rits. who found simple relationship between these two. The graph in Fig.3.3 shows the variation of dielectric constant and dielectric loss of water with change in frequency over a wide range of the latter. It will be seen from the curve that the dielectric constant remains nearly the same over a very wide range of frequencies.

Theory of Measurement

The operating principle of the capacitance type resistance meter is based on the change occurring in the dielectric constant between its moist and dry conditions. It has been observed that dielectric variation of hygroscopic materials having moisture is quite linear over a limited but useful range of 0% to 35% moisture content which corresponds to a change in relative humidity of 30% to 90% at 20°C.

The dielectric constant of water is 81 whereas the dielectric constant of most organic materials of vegetable origin such as textile fibres, paper, wood, soils, cereals concrete etc, is quite low, ranging from 22 to 50 in "bone dry" condition. Therefore, presence of a very small quantity of water in the materials causes considerable change in the dielectric constant of the mixture of the

two and it is this property of dielectric variation which is made use of in most of the capacitance or dielectric type moisture measuring instruments. Though the water absorbed by hygroscopic materials does not form a mixture in the *strict* sense, the free water as well as the water mechanically held in the pores of porous materials can be treated as forming a mixture with the solid material and the composite dielectric constant of such a mixture can be theoretically estimated.

Under ideal conditions, the dielectric constant of this type of mixture (ϵ_m) is given by the following relationship.

$$\epsilon_m = \epsilon_1 \delta_1 + \epsilon_2 \delta_2 \quad \dots \dots (3.4)$$

where ϵ_1 and ϵ_2 are dielectric constants of the two constituents, and δ_1 and δ_2 are the volume filling factors of each component forming the mixture, which is very nearly the case when water is absorbed or desorbed by a hygroscopic material to attain equilibrium with an ambient atmosphere.

From this equation, the presence of 1% of water in any substance will lead to an increase in dielectric constant of the mixture by 0.8 unit, and the variations are linear. Mixture containing systems encountered in

practices do not behave ideally and hence calibration curves are necessary for every system to be analysed. However, it should be emphasised that the "mixture law" proposed so far gives an accurate description of the dielectric behaviour of a heterogeneous mixture and for each individual case it is still necessary to determine the particular parameters. In general, the dielectric constant of any granular or fibrous material increases as its moisture content increases. The variation of dielectric constant with change in moisture content is the factor which makes it possible to utilise the capacitance changes for the measurement of moisture contents, as the dielectric constant is related to the capacity of a capacitor. The capacity change for a small increase or decrease in moisture content varies appreciably, depending upon the micro structure of the materials.

Description of Capacitance Type Moisture Meters

These meters have three constituent units, i.e.

- (i) Electrode system
- (ii) Electronic Circuit
- (iii) Indicator or Recorder

The sample is introduced into the electrode system so as to form a dielectric between the insulated plates forming a capacitor. The capacity change introduced into the electrode system due to change in moisture content of the sample is converted into a corresponding current or

voltage change by the electronic unit and is indicated by the indicator which is usually a calibrated microammeter.

(1) Electrode Systems

The geometry and design of the electrode system depend upon the nature of the sample and the type of measurement to be made. Plate type electrodes are found to be most suitable and are mostly used. One of the problems in the design of a parallel plate electrode system is the ^{presence}vention of "fringing" which causes error in the capacity value. There are theoretical formulæ to calculate the contribution of the "fringing effect" and it can be minimised experimentally by introducing a guard ring around the end of the plates. The guard ring should be maintained at earth potential and its associated electrode can be kept at a low potential with respect to earth, while the opposite electrode is at a higher potential. By this arrangement the "fringing" is confined to the guard ring and the opposite electrode keeps the electrostatic field straight between the upper and lower measuring electrodes. Some fluffy materials like cotton, raw wool, sands, saw dust, etc. require application of *uniform* pressure for maintaining a constant uniform packing density. However, it has been found that most of the materials in capacitive type moisture meters require very small pressures to give standard moisture content values.

(ii) Electronic Circuits:

Three types of circuit are used for measuring the small capacitance changes obtained in the electrode system:

- (A) Bridge Circuits
- (B) Resonance Circuit
- (C) Beat frequency circuit

(A) Bridge Circuits

The bridge circuit can be used to measure the small capacitance variations caused by the change in moisture content of the sample introduced to the electrode system. The use of a high frequency oscillator in this method gives the advantage that the impedance of the test capacitor is reduced to such a value that stability and accuracy can be obtained and very small increments in capacity due to small changes in moisture content can be measured.

(B) Resonance Circuit for Moisture Measurement:

This method utilizes the well known principle of the variation of voltage or current in a series or parallel resonant circuit near the resonant frequency. Over a limited portion of the resonance curve, the voltage or current varies approximately linearly with the unknown capacitance which is forming a part of the resonant circuit and whose capacity varies with change in moisture content of the sample. The range of moisture contents over which electronic measurements are absolutely precise depends on the nature of the sample but it is always limited to the

hygroscopic range, the most satisfactory results being obtained on materials in equilibrium with atmosphere of Relative Humidities of 30% to 90%. When the material is drier than this, the moisture is so tightly bound that it has a relatively small effect on the electrical properties and when the material is very damp the electrical characteristics are strongly influenced by factors other than the moisture content.

(C) Beat Frequency Circuit For Moisture Measurement

In this system two oscillators, one of fixed frequency, preferably crystal controlled, and the other a variable frequency type, are used. To the variable oscillator are connected the capacitor formed by the materials under test and a calibrated capacitor. Finally, both oscillators have the same frequency i.e. show a zero beat as indicated by the null detector which can be either a headphone or a meter. A circuit based on this principle has been used by Anderson for devising a moisture meter. Such a meter cannot be used for continuous measurement as measurement is not instantaneous.

Operating Considerations of Capacitance Type Moisture Meter

In order to get best results from these moisture meters, the following factors should be taken into consideration.

(i) Moisture Distribution

Moisture should be well distributed throughout the sample being tested and the moisture content should preferably be under 30%, depending upon the nature of the sample.

(ii) Presence of Electrolytes

Small amounts of electrolytes do not introduce appreciable error in the moisture measurement. But if the samples contain excessive amounts of additives in the form of electrolytes then these are likely to lead to erroneous results. As these additives will introduce dielectric losses causing the indicator to read higher, a separate calibration for such a sample may be necessary.

(iii) Temperature Effect

Temperature correction should be made if the temperature at which measurements are made is much different from the temperature for which the moisture meter is calibrated as the dielectric constant of water is affected by temperature changes.

(iv) Packing Factor

The sampling "Dielectric cell" should be packed to a constant density in order to get uniform results. It is usually best to pack a known weight of the sample in a fixed volume to get the same packing factor. On the whole, the packing density is not so important for capacity meters as for conductivity ones.

Relative Merits and Demerits of Capacitance Type
Moisture Meters

- (i) The calibration of the meter is not appreciably affected by the addition of small quantities of a number of electrolytes as experienced in industrial processes. The addition of acids or salts in a product may have no appreciable effect on its dielectric constant whereas the conductivity is considerably effected.
- (ii) A large change in dielectric constant occurs for small changes of moisture content in most of the materials, hence very good sensitivity can be obtained.
- (iii) It is not necessary that the material be in contact with the electrodes. As a matter of fact, it just touches only one of the electrodes in most processes. Hence this method is found most convenient for continuous measurement and control of moisture in industrial operations.
- (iv) The electrode system can be modified in different ways to meet the requirements of sampling of a large number of samples and thus its applicability has been made almost universal.
- (v) When subjected to abnormal temperature and tension variations, the calibration of the meter is affected but it should be noted that these variations seldom occur in operating conditions.

3.2 SONIC AND ULTRASONIC TECHNIQUES OF MOISTURE MEASUREMENT⁵

The absorption of sound is dependent on the medium through which it passes. In many solid materials the intensity of sound waves is affected by the quantity of water present in the sample. An audio frequency tone is generated by a phase shift generator and fed to a loudspeaker as shown in Fig.3.1. This generator is placed on one side of the web and a receiver or a microphone is placed on the other side to pick up the sound. The output of the microphone is amplified to a sufficient value to obtain a reading on the scale of a volt meter connected to the last stage of the amplifier. The amplifier output can be utilised to operate an electrically controlled mechanism arranged to effect the formation of the material of the web under measurement, so that it may be adjusted automatically if variations in moisture content occur. Martin and Moun field have made considerable improvements in the design of the sonic analyser.

Utilising the same principle of absorption, ultrasonic energy instead of audio frequency has been used for measurement of moisture content. Due to the higher frequencies, ultrasonic waves have special properties of reflection, refraction and absorption. They can be beamed and focused in a desired manner, and consequently a number of technical and industrial applications have been made.

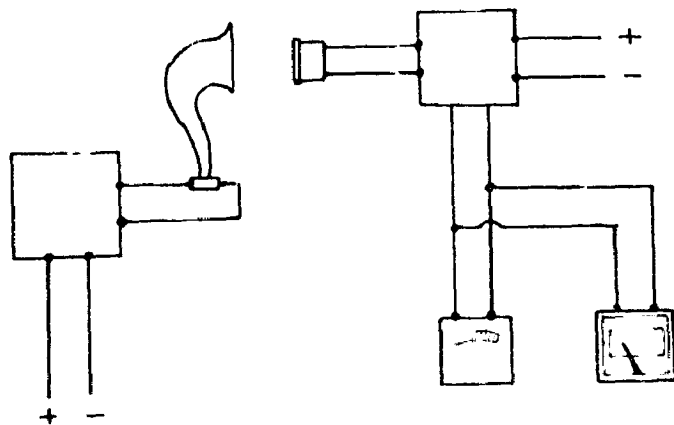


FIG. 3.4 SONIC MOISTURE METER

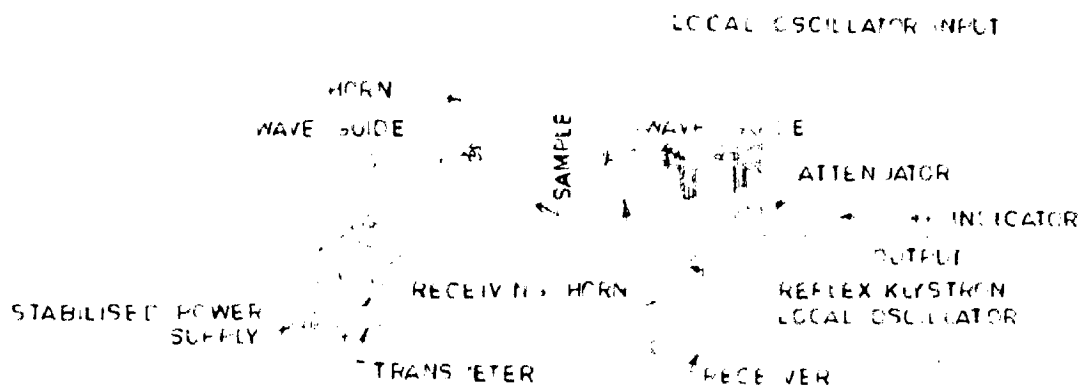


FIG. 3.5. GENERAL LAYOUT OF MICROWAVE MOISTURE METER

In ultrasonic devices the audio frequency generator is replaced by an ultrasonic generator comprising a radio frequency oscillator and piezo electric transducer i.e. a quartz or ceramic crystal. The microphone is replaced by a piezo electric quartz receiver having the same resonant frequency as the generator. The ultrasonic waves, after passing through the web of the material, are picked up by the piezo electric transducer and amplified by a suitable amplifier whose output is connected to a meter or recorder.

It has also been observed that the velocity of ultrasonic waves is dependent on the medium through which it passes and presence of water in a solid medium may influence it. Based on this principle, ultrasonic velocity measurements have also been used for determining bound water in aqueous solutions of electrolytes and non-electrolytes.

3.3 MICROWAVE ABSORPTION METHOD OF MOISTURE MEASUREMENT^{6,8}

It is well established that micro-waves behave in many respects similarly to light waves, obeying the same laws of wave propagation, reflection, absorption, refraction and diffraction. But the experimental techniques involved in the case of microwaves are quite different from those employed in optical systems. Electro-magnetic waves, including microwaves, have recently been applied

for investigating presence and structure of water molecules in crystals and solids. A brief description of the principles and techniques, involved in the measurement of moisture content is described here.

3.3.1 Method Based On The Change In Attenuation⁶

The dry sample does not absorb microwaves while the wet absorbs and hence there is a change in attenuation. This change in attenuation depends upon the quantity of water content in the sample. Therefore attenuator can be calibrated in terms of moisture content.

Theory

In the microwave region, many liquids and solutions have absorption peaks and associated regions of anomalous dispersion caused by orientation of the molecular dipoles in the electromagnetic radiation field. The frequencies of the absorption peaks are given by the following relation,

$$f_{er} = \frac{1}{2\pi\tau} \quad \dots (3.5)$$

Where

$$f_{er} = \text{the frequency of electromagnetic radiation}$$

$$\tau = \text{the relaxation time of molecular dipole}$$

The relaxation time τ is given theoretically by the following equation due to Debye.

$$\tau = \frac{V \cdot 3 \eta}{k T} \quad \dots (3.6)$$

Where η = microscopic viscosity of the liquid

v = volume of a molecule of the liquid

h = Boltzman constant

T = Temperature in absolute scale.

Water at room temperature has a viscosity of $\eta = 0.01$ poise, and radius of its molecule is 2\AA . Hence the relaxation time is given as

$$\tau = 0.25 \times 10^{-10} \text{ sec.} \quad \dots (3.7)$$

This value of relaxation time of water corresponds to a wave length of one centimeter. Though there is a wide divergence between the theoretical and experimental values of microwave frequency of maximum dielectric absorption, Debye's theory gives an idea of the order of frequency involved for investigating relative absorption by water molecules which were supposed to be spherical in deriving equation (3.6). For the case of water, it has been observed that the absorption band corresponds to a frequency of 2,450 Mc/s. It has been reported that there is a linear relationship between the moisture content and the absorption of micro-waves having a frequency of 2,450 Mc/s. As the absorption of microwaves will depend on the moisture content only and will not be affected by the presence of solid material, this method offers a unique method of moisture determination.

Description of the Apparatus:

The equipment consists of the following:

- (i) A constant source of microwave radiation of 2,450 Mc/s modulated by a square wave of 3 KC/s.
- (ii) A wave guide terminating in a horn and associated components.
- (iii) A microwave detector
- (iv) A microwave attenuator and amplifier
- (v) Indicating meter

The experimental arrangement is as shown in Fig.3.5. This is the usual transmitter-receiver combination, the specimen forming the absorbing medium. The most commonly used source of microwave radiation is the reflex klystron oscillator which works on the well known principle of velocity modulation and "electron bunching". With careful oscillator design, using high Q circuits and a highly regulated degenerative type of power supply, it is possible to achieve a frequency stability of an order sufficient for this purpose. However, by using an external high Q cavity, Pound has been able to control the frequency of microwave oscillators oscillating at 10,000 Mc/s within a few kilocycles per second. This oscillator gives a modulated power output of 0.5 watt and is coupled to a radiating horn by a quarter wave length system as shown in Fig.3.5.

The receiver consists of the receiving horn which is coupled to a 70 dB variable attenuator followed by crystal mixer, local oscillator, limiter discriminator, and final amplifier. The method of using the apparatus is to arrange the transmitter and receiver facing each other and spaced at a distance equal to the thickness of the sample or the wall. To begin with, the attenuator is adjusted to a certain reading on the indicator scale and the attenuation reading is noted. Then the transmitter unit is placed on one side of the sheet of the material or wall whose moisture content is to be measured. The receiver is placed on the other side, and is made to scan the surfaces of the sample vertically and horizontally for maximum reading on the indicator meter. The attenuator is then adjusted till the initial reading of the meter is obtained again. The difference between the two positions of the calibrated attenuator gives a measure of the moisture content of the sample only as there is no absorption of microwave energy by the sample in dry condition.

The moisture content value of the unknown sample is obtained from the calibration curve drawn earlier between attenuation readings and moisture content data obtained by standard oven drying methods. This type of moisture meter is capable of measuring water content in a large volume of the material, e.g. bales of cotton and jute, walls and slabs of concrete etc.

The method based on measurement of attenuation of the electromagnetic wave passing through the wet material appears to be most useful in laboratory as well as in industrial practice. Moisture content can also be determined by measuring the phase shift introduced by the wet material.

The main disadvantage of these methods, equally as of all other indirect methods of moisture content measurement, results from the strong dependence of density or thickness of tested material upon the result of its moisture content measurement. This arises from the fact that the measurement of moisture content being a ratio of two physical quantities—weight of water and dry substance—is based only on one parameter of the wet material (e.g. upon the value of its attenuation). Many attempts have been made to avoid this disadvantage by carrying out two separate measurements simultaneously e.g. by measuring the moisture content with microwave meter and the density of material with a nuclear radiation meter or by measuring the moisture content at two different frequencies—e.g. in RF and microwave bands. A metrological weakness of such a solution comes from the fact that readings on both instruments are more or less dependent upon water content but not upon the weight of dry material. An instrumental disadvantage consists in application of two different meters, that very often are complicated and expensive.

9.3.2 An Improved Microwave Method of Moisture Content Measurement

The disadvantages of the above method can be limited by measuring both the attenuation Δ and phase shift β of the electromagnetic wave-simultaneously.

Theory

The well known definition of moisture content determined on a wet weight basis w_v may be written as

$$w_v = \frac{v_w}{v_0 + v_w} = \frac{v_w \sqrt{v}}{v_0 \sqrt{v} + v_w \sqrt{v}} \quad \dots (3.8)$$

where v_w is the weight of water, v_0 is the weight of dry material, v is the volume of the wet sample. The density of wet material g may be written as

$$g = \frac{v}{v} = \frac{v_0}{v} + \frac{v_w}{v} \quad \dots (3.9)$$

Attenuation and phase shift of the electromagnetic wave passing through the sample of wet material are related to the thickness of the sample and to the dielectric properties of the material. The permittivity of the wet material is a function of its water content, density and physical properties (Strength of water binding). Thus, the measured values Δ and β may be presented in a general form

$$\Delta = F_1(v_0, v_w) \text{ and } \beta = F_2(v_0, v_w) \quad \dots (3.10)$$

In the simplest case, when it may be assumed that the wet material is a homogeneous substance and that the attenuation Δ and phase shift β are linearly related

to the weight of water and weight of dry substance the case most often met in practice, eq. (3.10) may be written in the form

$$\Lambda = t \left(\frac{w_w}{V} a_1 + \frac{w_o}{V} a_2 \right), \quad \dots (3.11)$$

$$\beta = t \left(\frac{w_w}{V} a_3 + \frac{w_o}{V} a_4 \right),$$

Where t denotes the thickness of the material layer, numerical coefficients a_n are specific for a particular material and its physical properties, Λ is the attenuation of the wet layer in dB and β is the phase shift in degrees. The numerical coefficients a_n are given for a volume of 1 cm³, because the values of w_w/V and w_o/V are also referred to this volume.

The following relations may be obtained easily by solving equation (3.11).

$$\frac{w_w}{V} = \frac{1}{t} \left(\frac{\Lambda a_4 - \beta a_2}{a_1 a_4 - a_2 a_3} \right) \quad \dots (3.12)$$

$$\frac{w_o}{V} = \frac{1}{t} \left(\frac{\beta a_1 - \Lambda a_3}{a_1 a_4 - a_2 a_3} \right)$$

By substitution of equation (3.12) into equation (3.8), the simple expression for moisture content may be written as

$$w_w = \frac{\Lambda a_4 - \beta a_2}{\beta (a_1 - a_2) - \Lambda (a_3 - a_4)} \quad \dots (3.13)$$

It may be seen from the above expression that the moisture content determined according to this expression does not depend upon either thickness of the material or upon density of the material.

Instead of solving the complicated analytical relations, an empirical method may be used for calculating the numerical coefficients, based on measurements of the phase shift and attenuation introduced by the material of different density and moisture content, for constant thickness of its layer. The values of a_n calculated for building sand at temperature of 20° and at frequency of 9.4 GHz are as follows. $a_1 = 299.27$, $a_2 = -1.42$, $a_3 = 8177.43$, $a_4 = 421.55$. Substituting these values in equation (3.13), we have

$$\epsilon_w = \frac{4.21A + 0.014 \beta}{3.01 \beta - 77.56A} \dots (3.14)$$

Where A is the attenuation of an arbitrary sand layer expressed in dB, and β is the phase shift introduced by the layer, in degrees.

Fig.3.6 gives the block diagram of the complete measuring system. Inclusion of a thermometer probe sensing the material temperature to the calculating unit enables the correction of a_n values, according to the material temperature. The purpose of the calculating unit is continuous calculation of moisture content according to equation (3.14). The output of this unit is independent upon density of wet material, upon its layer thickness & upon its temperature. In this method "modulated subcarrier technique" is used.

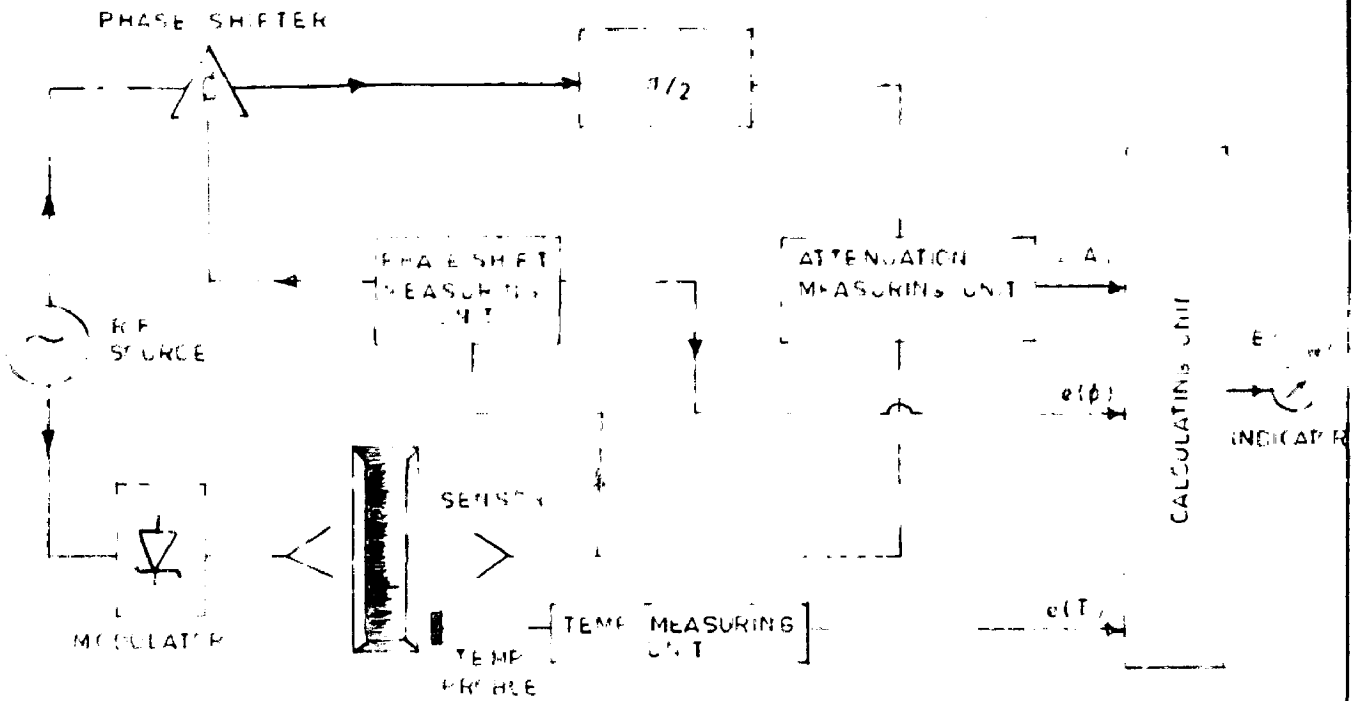


FIG. 3.6. BLOCK DIAGRAM OF THE TWO PARAMETERS MEASURING SET UP WITH A CALCULATING UNIT AND TEMP. COMPENSATING DEVICE

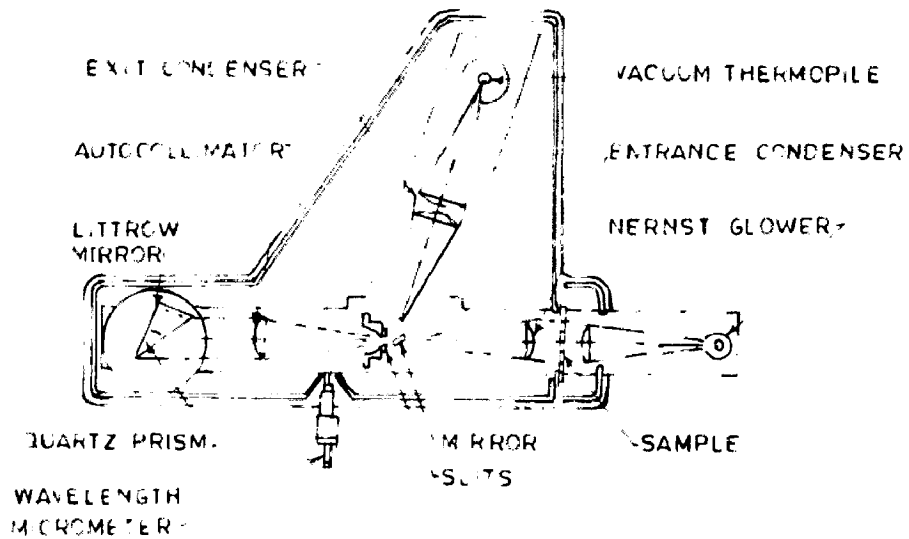


FIG. 3.7. SCHEMATIC DIAGRAM OF A SINGLE BEAM INFRARED SPECTROMETER.

Limitation in application of this method, as with all those shift measuring methods, results from the ambiguity of the phase shift measurement. This means, that in the case where considerable changes of phase shift are introduced by wet material under test (when $\phi > 2\pi$), inaccuracy of the calculation of the moisture content could be very high and might hide the advantages of this method.

3.4. MEASUREMENT OF WATER BY ELECTROLYSIS⁶

The principle of operation and method of moisture measurement is described in brief.

PRINCIPLE OF OPERATION

An electrolytic moisture meter has been developed which is based on the principle of absorption of water in a suitable hygroscopic material followed by electrolysis of the water to oxygen and hydrogen, the electrolysis current serving as a direct measure of water content. In accordance with Faraday's law of electrolysis, 0.5 mole of water (9.01 grams) requires 96,500 coulombs of electricity. The electrolysis current is proportional to the number of moles of water absorbed per unit time. Analysis of water is accomplished in a special cell which combines absorption with electrolysis. The absorbed water is quantitatively electrolysed at the platinum electrodes by application of a dc voltage greater than the decomposition potential of water.

In an electrolytic moisture meter a weighed solid sample i

placed in a small Teflon oven which is heated by a radio frequency field. As the moisture vapours emerge from the sample, they are entrapped by a carrier gas, which is usually nitrogen and which is kept flowing through the upper portion of the oven at a constant rate of about 100 cc/min. This carrier gas then transfers the vapours of the sample to the sensing elements, i.e. Platinum electrodes, of the cell. The mass flow rate of the moisture is represented linearly by the electrolytic cell current and an electromechanical integrating motor provides a direct reading in micrograms of water. It takes about 10 minutes to complete a cycle of one measurement. A variable timer used to control the test cycles permits complete automatic operation of the instrument. Accuracy of the instrument is normally limited only by the precision of the electrical and flow meter components. It is not affected by the exact value of the cell voltage as long as the voltage remains high enough to ensure complete and quantitative electrolysis of absorbed water.

3.5 APPLICATION OF INFRA-RED SPECTROSCOPY FOR MOISTURE MEASUREMENT^{6,9}

The technique of infrared absorption spectroscopy is one of the most versatile and reliable methods of the detection and quantitative measurement of water content

of various substances. A simplified picture of the process of the interaction of infrared radiation with matter is given here. Consider a diatomic molecule, say AB. This molecule may vibrate along the direction AB as if the atoms are joined by an elastic spring with a certain natural frequency "f" which depends upon the force of the binding and the "reduced mass" of the system AB. A polyatomic molecule will have similar vibrations between the individual bonds of the atoms of the molecule. A molecule of N atoms will have in general 3N degrees of freedom which means, roughly that 3N ordinates are necessary to describe the dynamical system of the complex molecule. Now the molecule may have translational motion which requires 3 co-ordinates for its specification, and also, the same molecule can rotate as a whole, which requires another three coordinates. This leaves us with $(3N-6)$ degrees of freedom which must necessarily be associated with the vibrations of the various atoms of the molecule. Each of these vibrations are "Quantized". If now infra-red radiation having a continuous range of frequencies is incident on the molecule, there are some frequencies which correspond to the characteristic molecular vibrations of the molecule. Under such conditions, resonance takes place and energy is absorbed by the molecule, the dipole moment acting as the coupling mechanism.

The energy so absorbed by the molecule is subsequently lost by collision with other molecules (which explains the heating mechanism of the infra-red rays), and the infrared radiation is thus weakened or absorbed at certain definite frequencies which are characteristic of the molecule. The infrared absorption spectra of the material is thus obtained. The magnitude of the absorption can be directly related to the amount of a component present in the sample.

Infra-red Spectrum of Water

The infra-red spectrum of water molecule has been investigated by a number of workers with a good degree of accuracy and resolution. Mecke has made a complete analysis of the rotational spectra of the water molecule. Nielson has made a thorough study of the near infra red (bolometric region) spectra of water vapour. The near infra red absorption spectrum of liquid water has been subjected to an accurate analysis by Curcio and Petty who used sensitive lead sulphide cells as detectors. They concluded that five relatively prominent bands of absorption spectra exist for liquid water in the region 0.7μ to 2.5μ . When present as moisture content in solids and liquids water molecules are always in a polymer form such as $(H_2O)_2$, $(H_2O)_3$ or other higher complex form. Water vapour, however exists only as a monomer, i.e., as H_2O . The wave length of maximum absorption of the infra-red spectra depends on the polymeric form of water. It also depends upon

the hydrogen bonding between the water and other polar molecules. Hence, the region of infra-red spectra to be employed for investigating the presence and quantity of water depends upon the system in which the amount of water to be determined is held.

Instrumentation

The instruments for recording and measuring infrared absorption spectra can normally be divided into single beam and double beam instruments. In the former, the energy of radiation is measured after passing through the absorbing medium. It is quite useful for the routine work. In the double beam instrument, the ratio of the intensity of radiation transmitted by the sample to the intensity of radiation without the sample is obtained directly. This observation is simpler to interpret and it takes into account many spurious effects. The important constituent units of a single beam infrared spectrometer are:

- (i) Source of Radiation
- (ii) Monochromator
- (iii) Detector and amplification system

These are shown schematically in Fig.3.7.

(1) Infra-red Source

Starting from the visible region upto 2μ , a tungsten filament projection lamp can be used. Infra-red radiation can be obtained by using a Nernst filament lamp

which gives maximum energy of radiation at 7.1μ . Another quite common source is glabar which essentially is a rod of silicon carbide. Maximum energy of radiation for a glabar is in the region of 1.8μ to 2μ . Some other sources are also sometimes used. Smith has described the use of a carbon rod as a source of infra-red radiation. The carbon rod is heated electrically in vacuum upto 1800°C . This source is suitable for longer wave length (more than 5μ) where its emission is comparable with that of a glabar.

(ii) Monochromator

The source image is first focused on the entrance slit of the monochromator. The function of the monochromator is to disperse the radiation. The spectrum after dispersion, is allowed to fall on the exit slit which is sufficiently narrow and hence permits the radiation of a very narrow wave length range to be studied at a time. The selection of a suitable prism material is of great importance. The material of the prism chosen necessarily depends upon the wavelength range employed for a particular investigation. Rock salt Prism covers a wide range, but suffers from a low dispersion near 3μ . In near infra-red, Fluorite and Lithium Fluoride have better dispersion properties. Quartz is unsuitable in the region near 3μ because of occluded water which gives rise to an extra absorption band at about 2.9μ . Multiple prism systems have been used to increase dispersion.

(iii) Detection and Amplification

The radiation coming from the monochromator system and falling on the exit slit is then focused upon a device which indicates the amount of energy in the radiation. Thermopiles and bolometers are frequently used for this purpose. A thermopile is a combination of a number of thermocouples which are linked together. The radiation falls on one of the two metal junctions producing an emf. This emf. can be amplified and recorded using photoelectric relay amplification as described by Wright or electronic amplification can be used. A rapid response thermopile for use with infra-red spectrometers has also been designed by Roers and Dacus. The bolometer, typically a strip of blackened platinum foil whose resistance changes proportionally to the incident radiation is also commonly used. Bolometers have a better response characteristic than a thermopile system and offer good advantages where an infra-red spectrum is to be scanned or timed. A.C. amplifiers are used for amplification. Other types of detectors have also been used. A photo cell offers a better sensitivity but suffers from the limitation of range. The double beam infra-red spectrometer has acquired great importance because of the many advantages that it offers. In these instruments, the affect of the inconstancy of the source and the absorption due to air and moisture is cancelled out and great simplicity results in the operation of the equipment and the interpretation of the data. An interesting and very useful application of the double beam instrument is in differential spectroscopy which permits one to obtain the spectrum of one of

the constituents (such as moisture present in the sample), from a mixture of two components.

3.6 NUCLEAR MAGNETIC RESONANCE METHOD^{7,10}

There are three well defined branches of radio frequency spectroscopy. These are (i) electron paramagnetic resonance (ii) microwave spectroscopy and, (iii) nuclear magnetic resonance. The nuclear magnetic resonance technique, popularly known as N.M.R., is based on the absorption of radio frequency energy by the nucleus of an atom placed in a constant magnetic field. This N.M.R. technique has a number of applications in chemical analysis connected with product identification in petroleum and chemical industries, as well as the measurement of moisture content of hygroscopic solids. The application of N.M.R. to moisture measurement meets the long-sought industrial requirement for a quick, accurate, and non destructive method of obtaining moisture content and control of raw materials and finished products.

Theory

In addition to mass and charge, some of the light atomic nuclei possess the extra characteristic of spin. The most common atoms are those of hydrogen, deuterium, tritium, helium, lithium, beryllium, boron, carbon, nitrogen, phosphorus, chlorine, etc. N.M.R. data of these elements are shown in Table II. The property of spin of the atom

N.M.R. DATA FOR A FEW LIGHT ELEMENTS

Isotope (1)	ν (2)	N.A. (3)	Relative Sensitivity (R.S.) (4)		Magnetic Moment μ (6)	Spin in multiples of $h/2$ (7)
			at constt. field (4)	at constt. frequency (5)		
H ¹	42.577	99.98	1.000	1.000	2.79270	1/2
H ²	6.536	1.56×10^{-2}	9.64×10^{-3}	0.409	0.85738	1
H ³	45.414	-	1.21	1.07	2.9788	1/2
He ³	32.434	$10^{-5} - 10^{-7}$	0.443	0.762	-2.1271	1/2
Ia ⁶	6.275	7.43	6.51×10^{-3}	0.392	0.72191	1
Ia ⁷	16.547	92.57	0.294	1.94	3.2360	3/2
Be ⁹	5.983	100.00	1.39×10^{-2}	0.703	-1.1774	3/2
B ¹⁰	4.575	18.83	1.99×10^{-2}	1.72 1.60	1.8006	3
B ¹¹	13.66	81.17	0.165	0.261	2.6880	3/2
C ¹³	10.705	1.108	1.59×10^{-2}	0.251	0.70216	1/2

1	2	3	4	5	6	7
H ¹⁴	3.076	99.635	1.01x10 ⁻³	0.193	0.40957	1
H ¹⁵	4.515	0.365	1.04x10 ⁻³	0.101	-0.28304	1/2
O ¹⁷	5.772	3.7x10	2.91x10 ⁻²	1.58	-1.8930	5/2
P ³¹	17.235	100	6.64x10 ⁻²	0.405	1.1305	1/2
Cl ³⁵	4.172	75.4	4.71x10 ⁻³	0.490	0.82069	3/2

W - N.M.R. frequency in Mc/s for a 10 kilogauss field.

NA - Natural Abundance

R.S. - Relative Sensitivity for equal number of nuclei

n - in multiples of the nuclear magnetron.

is the basis of the phenomenon of nuclear magnetic resonance. If those nuclei which have a magnetic moment and a spin "I" are placed in a homogeneous magnetic field, say H, they behave like minute magnets having random orientations and align themselves, depending upon the particular nuclei (e.g. hydrogen nuclei), either parallel or antiparallel to the direction of applied magnetic field. In addition to this, they also precess about the applied magnetic field analogous to the precession of a gyroscope spinning in the earth's gravitational field. The energy difference E between these two levels is expressed as

$$E = 2 \mu H \quad \dots \quad (3.15)$$

and the precession frequency, W, called Larmor frequency, is given as

$$W = \frac{2 \mu H}{h} = \nu H \quad \dots \quad (3.16)$$

where ν = the gyromagnetic ratio and is equal to

$$\frac{2 \mu}{h}$$

and h is Plank's constant

If these precessing nuclei are now subjected to a radio frequency field placed at right angles to the applied magnetic field H, and if the radio frequency and Larmor frequency W are equal, resonance occurs and the radio frequency energy is absorbed by the nuclei in proportion to their number. The quantity of radio frequency energy absorbed gives a measure of the abundance of hydrogen

nuclei which in turn can be used as a measure of moisture content in a sample. The magnetic moment of the proton (Hydrogen) is 1.4×10^{-23} erg/g and thus for a magnetic field of 10,000 gauss, the Larmour frequency ω equals 42.4 Mc/s. This frequency can be generated by standard electronic techniques.

N.M.R. Apparatus and N.M.R. Moisture Analyser

The phenomenon of nuclear magnetic resonance was first experimentally demonstrated by Purcell and Bloch. A number of N.M.R. spectrometers have been developed commercially and a large number of the laboratories and industries are using them. The basic apparatus for NMR. experiments is rather simple and consists of a powerful magnet having a very uniform magnetic field of about 10,000 gauss, a radio frequency oscillator, some form of radio frequency detector, indicator or recorder as shown in fig.3.8. For hydrogen nuclei however, a field strength of 2,000 to 3,000 gauss appears to be most commonly used. The magnet may be of the permanent or electro type, but in both cases sweep coils are wound around the large pole pieces so that the field strength H of the magnet can be varied continuously over a small range. The size of the poles must be large enough to enable the field passing through the sample to be homogeneous, otherwise the intensity of the absorbed radio

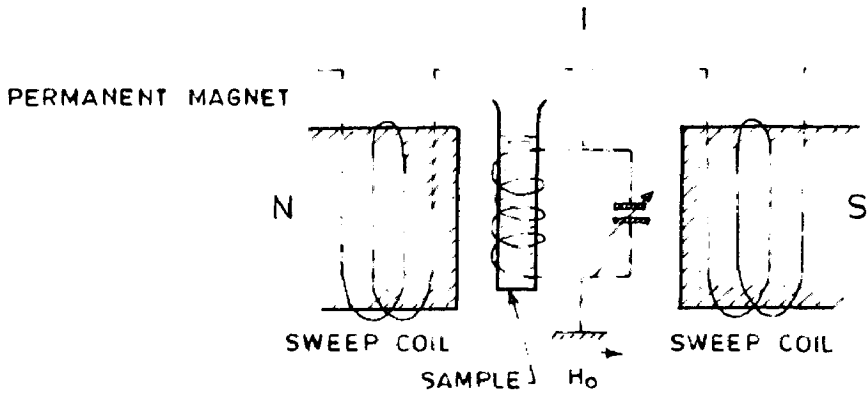


FIG. 3-8. SCHEMATIC DIAGRAM OF A BASIC N.M.R. APPARATUS

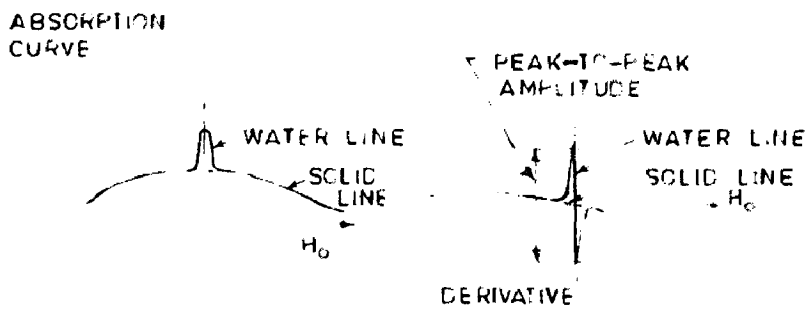


FIG. 3-9. N.M.R. SIGNAL FROM LIQUID WATER SUPERIMPOSED ON THE BROAD SIGNAL DUE TO SOLID CONTAINING THIS WATER

frequency signal will not be proportional to the number of nuclei present in the sample. A permanent magnet having a field strength of 1,750 gauss and poles of 16 inch diameter with 2 inch air gap was used by Conway, Cohen and Smith for measuring moisture in some solid materials. The radio frequency oscillator employed by these researchers has a frequency in the range of 100 Kc/s to 40 Mc/s, depending upon the magnetic field used for the experiment.

As there is a linear relationship between the resonance frequency ν and the magnetic field H , the N.M.R. spectra can be expressed as intensity of absorption plotted against ν at fixed value of the magnetic field H , or against H , keeping ν the frequency unchanged usually the resonance of a substance is measured in terms of precession speed at which the nuclei flip over. In practice, it has been found better to keep the frequency constant, and sweep through the magnetic field (by varying the magnetic field with the sweep coils) till resonance is observed. In studies involving liquid water, N.M.R. has been employed in two fields known as high resolution and low resolution techniques. In the high resolution technique, protons associated with different groups can be differentiated, though the actual spectra obtained depend on the system to be examined and are also considerably influenced by hydrogen bonding and by proton exchange reactions. With the low resolution techniques, it is rather difficult to distinguish between proton signals from water and those from other hydrogen containing substances in the liquid

phase. However, there is a sharp signal from the liquid water superimposed on the broad signal from the solid as shown in Fig. 3.9, obtained by a low resolution apparatus. Either peak to peak amplitude or the line width of the absorption line can be used as a measure of the water content. In N.M.R. line width (Fig. 3.10) is defined as the width at half the peak amplitude on the absorption curve, which is similar to a resonance curve of a tuned circuit excited by a sine wave. Absorption line width is related to the hydrogen mobility in the sample and the homogeneity of the magnetic field over the volume of the sample. In addition, the shape of the line is influenced considerably by the chemical and physical state of the hydrogen in the sample. The peak to peak amplitude method appears to be more reliable since small differences in water content have a greater effect on the amplitude than on the line width. On the other hand, in limited ranges where marked changes in line width are observed, this may give more accurate results. The theory of NMR leads one to expect a linear relationship between peak intensity of nuclear absorption and the moisture content provided the magnetic environment of the hydrogen nuclei is independent of the water content. The source of variation from linearity in low moisture content ranges might be due to the specific orientation of the initial water absorbed.

In general, liquids produce very narrow resonance lines of the order of a few milligauss, while solids produce line widths of the order of several gauss.

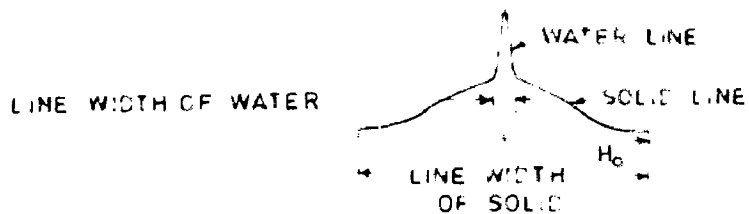


FIG. 3-10. LINE WIDTH OF AN N. M. R. SIGNAL

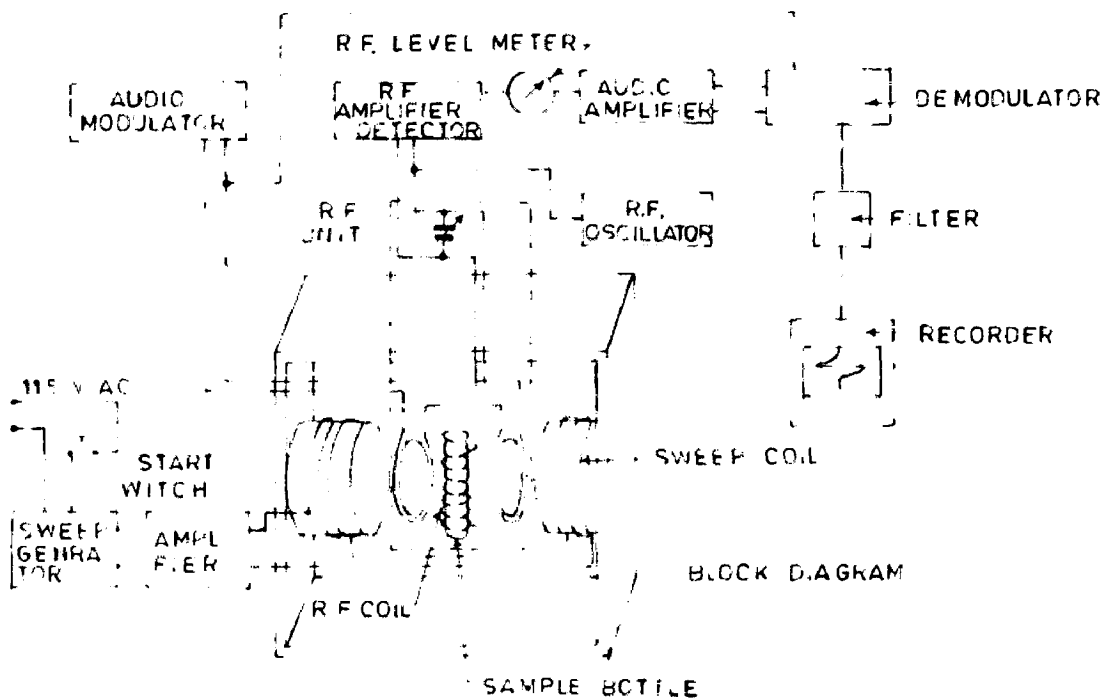


FIG. 3-11. DIAGRAM OF AN N. M. R. MOISTURE ANALYSER

N.M.R. equipments are, therefore, classified according to their ability to resolve a line of certain width. The resolution is expressed as the maximum inhomogeneity in percent of dc field strength over the volume of the sample. A high resolution apparatus has a magnetic inhomogeneity of one part in 10^5 to 10^8 , and in a low resolution technique the magnet has an inhomogeneity of one part in 10^5 to 10^6 . For high resolution, the sample volume is about 1/10th of a cc or less, whereas for low resolution apparatus it is as much as 50 cc. Thus, liquids with narrow lines require high resolution while solids with wider lines can be studied with ^{low} resolution techniques.

A simplified diagram of the N.M.R. analyzer is shown in Fig. 3.11. The permanent magnet assembly is the core of the equipment. A weighed quantity of the sample kept in some non magnetic container usually made of glass or ceramic, is placed between the highly homogeneous field of the permanent magnet and surrounded by an r.f. coil in such a way that the field thus produced is normal to the main field of the magnet. This radio frequency coil forms part of a sharply tuned parallel resonant circuit. The magnetic field of the permanent magnet is varied by adjusting a small current through the sweep coils wound on the poles to such an extent that there is a maximum absorption of the radio frequency energy

by the nuclei in the sample while changing from the parallel to anti-parallel position. This absorbed radio frequency energy is detected, amplified and recorded by the r.f. detector amplifier and recorder, the last being usually an oscillograph. The electronic circuit used by Aikman and his collaborators is that of the r.f. bridge type. To facilitate the observation of resonances of complex character and for searching for unknown lines, a spectrometer that operates with a varying frequency, while the magnetic field is held constant, is of considerable use. Such a radio frequency spectrometer with a bridge circuit has been developed by Pound and Knight.

The disparity between the line widths of hydrogen in a sorbed state and hydrogen in combination with the solid in which it is absorbed or adsorbed makes it possible to obtain an accurate measurement of the moisture content of hygroscopic materials. The N.M.R. analyser, however, records the derivative of the absorption curve and the peak to peak amplitude of this derivative curve is a measure of the moisture content.

This derivative curve is obtained by modulating the absorption curve by the super-imposing on the swept dc field of the pole pieces of the homogeneous magnet a small square wave of constant amplitude and low frequency.

The peak to peak amplitude has to be plotted against direct moisture values to give a calibration curve. These calibration curves for most of the materials are usually linear above 5% moisture content, but below this level greater curvature becomes perceptible, as shown in fig.3.12. This effect is attributed to greater interaction of the absorbed water with the solid material when small quantities of water are present. Such low moisture content measurement can be made by measuring the line width of the water signal as an alternative measurement as suggested by show, Elsker and Kunzman. By using a high resolution N.M.R. apparatus, it has been possible to differentiate between the free and bound water as shown by Shooley and Alder. The time required for one analysis is 30 to 60 seconds. Most of the apparatus at present in use seems to be suitable for hygroscopic material in general, over a wide moisture range (5% to 100%), and have an accuracy of the order of 0.2%. Some workers have shown the possibility of controlling the moisture content of wet materials by using N.M.R. equipment.

Since hydrogen (proton) has the highest sensitivity of any nuclear species to detection by N.M.R., this technique appears to offer a rapid, non-destructive method of estimating moisture-content over a very wide range with great accuracy. Dissolved organic compounds, bound water, etc, affect the signal absorption.

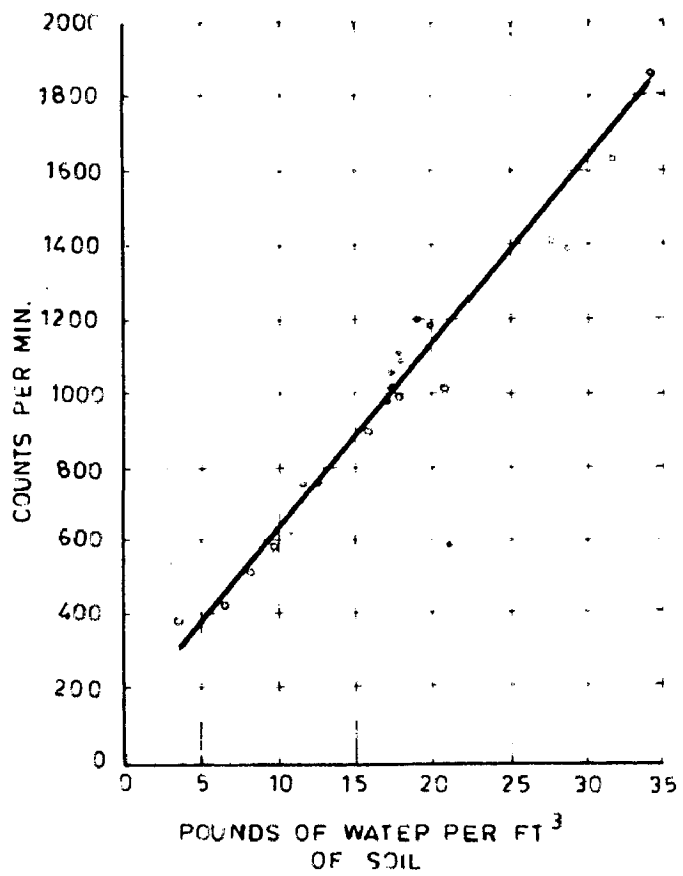


FIG. 3.12. CALIBRATION CURVES OF AN N.M.R. MOISTURE ANALYSER

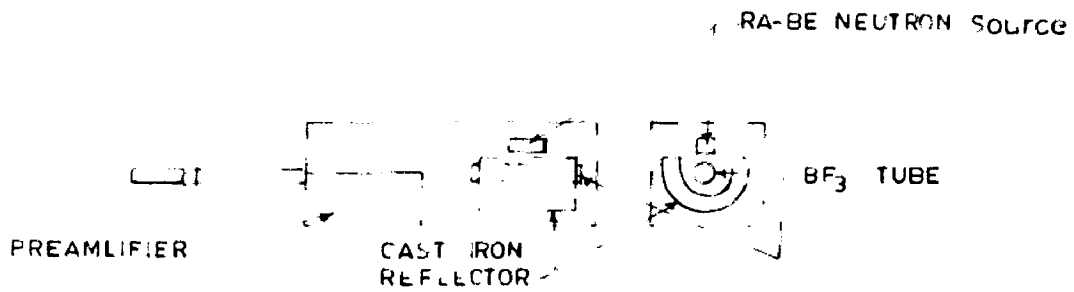


FIG. 3.13. LAYOUT OF NEUTRON MOISTURE METER FOR CONCRETE

The particle size and packing in the case of granular solids are stated to have no effect on the signal absorption, but it is essential to have a constant and correct weight of the sample. The main factor affecting its universal application in scientific laboratories and industries is the rather high cost of the equipment involved.

3.7 NEUTRON SCATTERING METHOD OF MOISTURE DETERMINATIONS PRINCIPLE

When fast neutrons are emitted from a source and projected into a material, they are scattered by the atoms of the material, losing energy and becoming slow neutrons. It has been experimentally established that among the common elements hydrogen is most effective in slowing down neutrons, i.e. the scattering cross section of hydrogen for fast neutrons is bigger than any other common element (because of the lowest atomic weight among the inorganic materials). Hence, if fast neutrons are projected into a moist material, a slowing down of neutrons will take place depending upon the quantity of hydrogen present, which in turn is proportional to the moisture content. Now, if a suitable counter is placed near the sample which has been irradiated by fast neutrons, the radiation produced by the slow neutrons should give a measure of the moisture content of the sample. If the solid material contains hydrogen in some other form in addition to its presence as a constituent of water

alone, the neutron count will be proportional to the total hydrogen content and not merely to the moisture content. It has been estimated that 0.1% of hydrogen has approximately the same effect on the neutron count as 1% of water. It is, therefore, desirable to know the chemical composition of the material whose moisture content is to be measured in order to interpret correctly the data obtained by neutron scattering.

It is well known that a mixture of radium and beryllium emits neutrons and that neutrons from such a source can be used to activate a metal such as Indium.

$I_n^{115} + n \rightarrow I_n^{116}$ which is radioactive and emits β particles with a half life of 54 minutes. It is known that indium exhibits large "water-effect" and, therefore, in this case neutron scattering would be expected to produce β -activity dependent on water content. The absorption cross section of I_n^{116} for slow neutrons of the order of 0.025 ev is 200 barns, and for fast neutrons of the order of 1.0 ev is 0.1 barns. This effect of an hydrogenous medium on neutron distribution is made use of in measurement of moisture contents in soils and the like materials.

Development of the Apparatus

Spinks, Lane and Torchinsky were the first to suggest the application of neutron scattering for measurement of moisture content in solids, especially soils

and clays. These instruments have been widely applied in the field of Civil Engineering where rapid measurements of moisture content have to be made e.g. in such materials as soils, clays, concrete-aggregates etc. The apparatus used by Spinks in preliminary experiments and subsequently developed into a neutron meter as shown in Figs. 3.13^{2.3.14} & 3.14. A 250 milli curie Ra-Be neutron source was separated from a square of indium foil by paraffin wax capped with a piece of cadmium. The cadmium foil served to prevent the direct access of slow neutrons to the indium foil. The whole arrangement was placed in a glass test tube (which was changed to aluminium later on) mounted vertically in a breaker of jumbo clay. The indium foil was activated for 70 minutes and then counting was commenced using a thin window Geiger counter connected to a scaler and register. The results showing the variation of induced radioactivity with moisture content are plotted in figs. 3.15 and 3.16. These results indicate that the induced radioactivity shows a strong dependence on the moisture content of the soil. It was found later on that the irradiation time can be reduced to five minutes only by using 4 inch square of indium foil, this arrangement having the added advantage that much smaller (50 mc) Ra-Be source can be used. The apparatus has been used for moisture measurement of sand and similar materials.

Gardner and Kirkham have devised a more compact

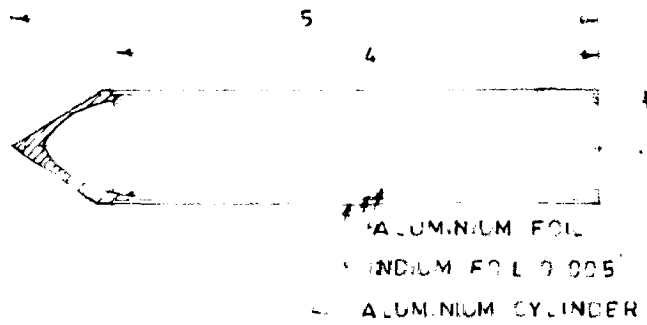


FIG. 3-14. ANOTHER APPARATUS FOR DETERMINING MOISTURE

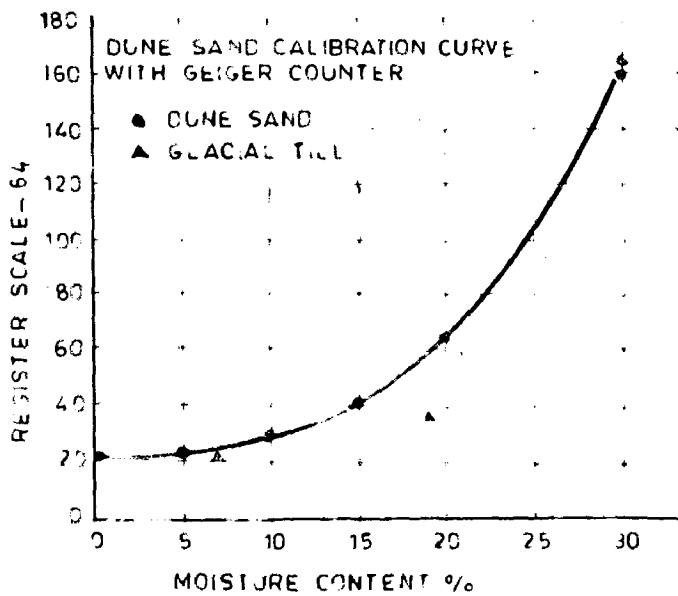


FIG. 3-15. INCREASED RADIOACTIVITY VERSUS MOISTURE CONTENT, RADIOACTIVITY MEASURED USING SCALE OF 64 SCALER.

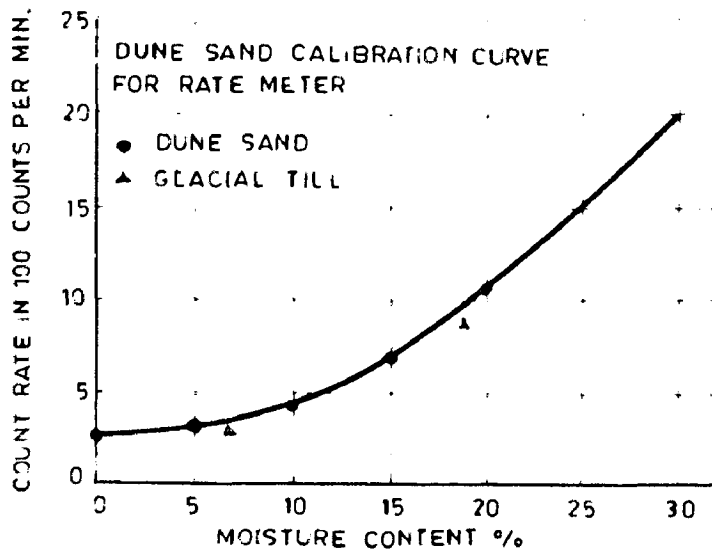


FIG. 3.16. INDUCED RADIOACTIVITY VERSUS MOISTURE CONTENT RADIOACTIVITY MEASURED USING RATE METER.

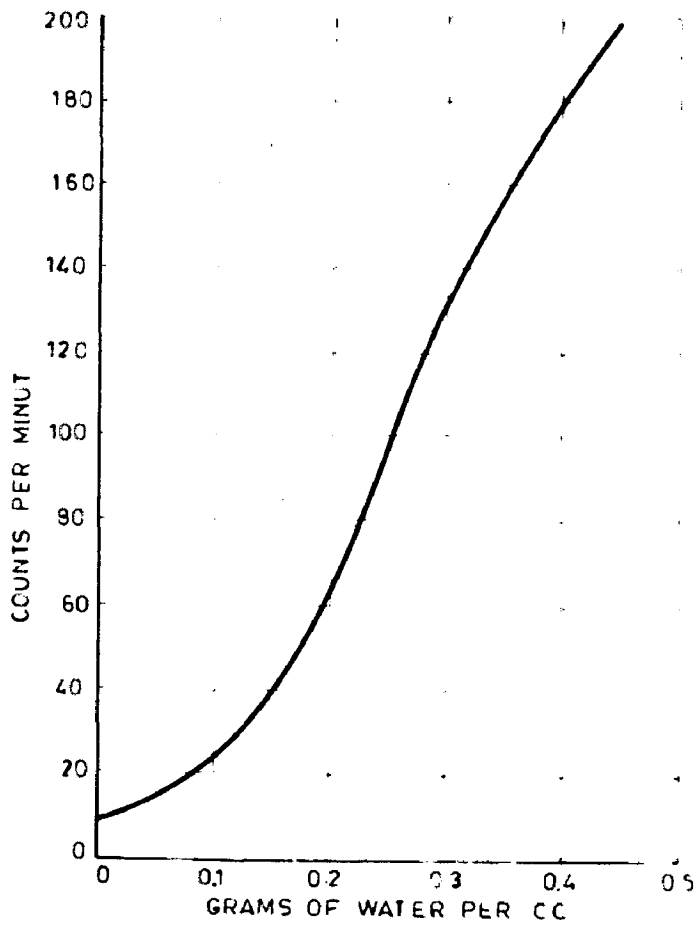


FIG. 3.17. GRAPHS SHOWING RELATIONSHIP BETWEEN NUCLEAR COUNT AND MOISTURE CONTENT

unit containing a mixture of polonium and beryllium as source of fast neutrons. The mixture has a half life of 140 days and a strength of about 10^4 neutrons-second. It was placed in a metal cylinder 17 mm in length which was inserted into a hole made in the material when making the analysis. A slow neutron counter containing borontrifluoride was located on top of and concentric with the fast neutron source. Pulses from the counter were amplified and recorded. Measurements were made after lowering the neutron source and counter into a hole drilled in the soil. Experiments were made with five different soils with densities varying from 62.4 lb/ft^3 to 94.4 lb/ft^3 . The results of the measurements showed that definite relationship exists between the neutron count and moisture content as shown in Fig. 5.17. When used on mineral soils, the method seemed to be unaffected by the temperature composition or concentration of the soil. The presence of organic matter affects the values, as, in effect hydrogen is determined by this method.

Applications of the neutron moisture meter have been extended to field problems by Pauliv and Spinks in which measurements are required to be made by placing the equipment on the surface of soils and concrete aggregates. Unlike the earlier neutron meters which had their probes immersed inside the wet material, the probe in this case lay on the surface of the material. This tends to reduce the volume that is effective in slowing down neutrons and hence makes the arrangement less sensitive.

The main chemical constituents of cement and concrete are a series of compounds comprising the elements calcium, aluminium, silicon, magnesium, iron, oxygen, sodium, potassium, sulphur and hydrogen etc. The effect of water in concrete on the relative thermal neutron-count is shown in table III. The neutron meter was finally calibrated for concrete by using specially made up samples.

TABLE III

EFFECT OF WATER IN CONCRETE IN RELATIVE THERMAL NEUTRON COUNT

Weight of Concrete in lbs.	Water lb/ft ³	Relative Thermal Count
Cylinder No.1 (18" dia., 8.3" depth)		
118.81	17.7	2.60
110.98	10.5	1.54
103.81	5.1	0.52
Cylinder No.2 (18" dia., 8.75" depth)		
112.50	16.6	2.62
111.26	15.5	2.23
109.94	14.6	2.07
107.88	13.0	2.03
106.94	12.2	1.88
100.06	6.9	1.00

Most materials vary in density as well as in moisture content, so that moisture cannot be measured as an independent variable unless the density of material is known. Response for a given moisture content increase with increase in the density of the soil (Fig₃18). This is due to isotropic scattering of fast neutrons. One method of determining the density is to employ a gamma source and direct the gamma ray beam into the material simultaneously with the neutron beam. The number of gamma rays reflected by the material or transmitted through the material is in inverse function of its density.

In the system shown in Fig₃19, the measuring head contains a neutron source detector assembly in one section and a gamma source detector in another compartment. The neutron reflection measurement provides a signal which is directly proportional to a volumetric moisture percentage. The gamma reflection measurement provides a signal which is directly proportional to density. These independent signals are sent to an electronic unit where they are scaled to kilograms per meter and presented simultaneously to a simple ratio computer. The ratio computer output signal is presented continuously in terms of percent moisture by weight and the electronic unit also provides a proportional voltage signal for driving a recorder or a moisture control system.

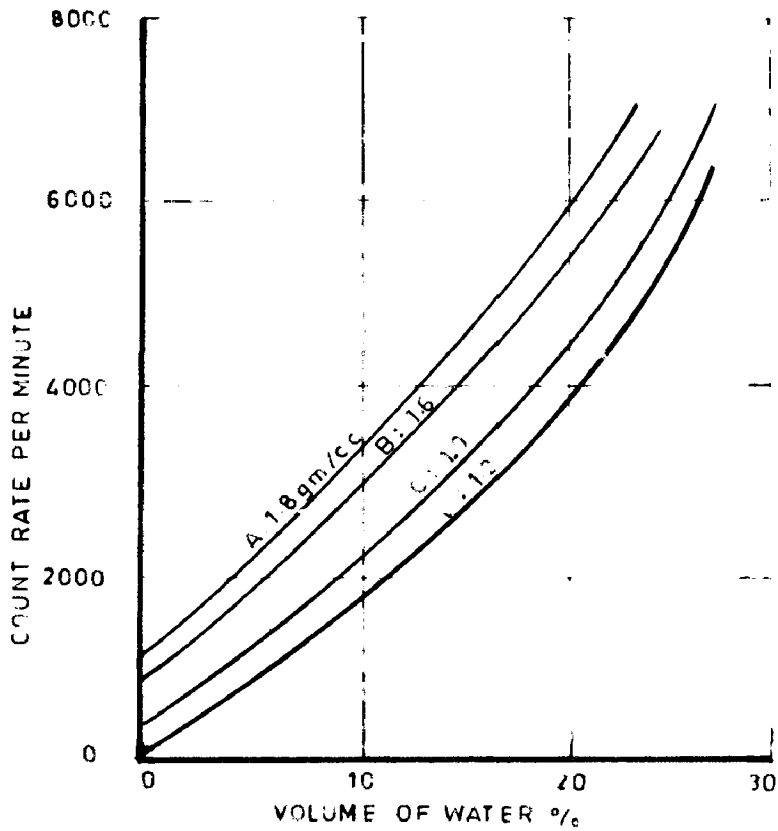


FIG. 3.18. EFFECT OF DENSITY OF SOIL ON THE COUNT RATE

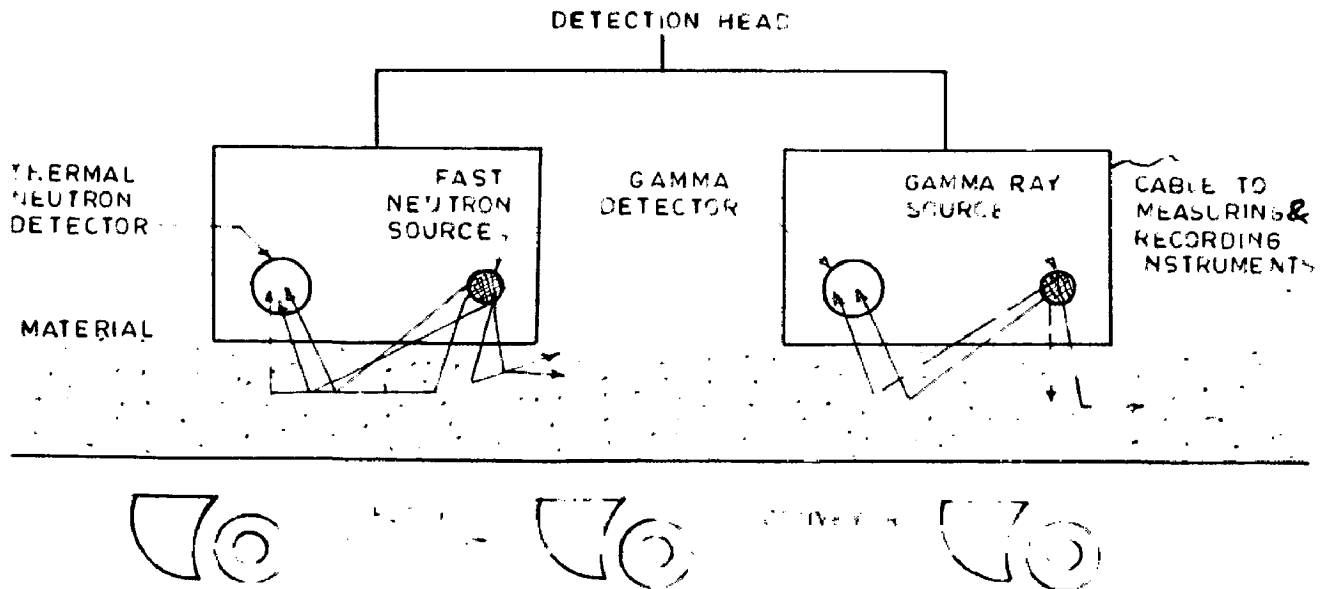


FIG. 3.19. NEUTRON SCATTERING MOISTURE METER

This neutron method of moisture measurement offers the advantage of not contacting the material being measured. There are no probes to clean and maintain, there is no danger of contaminating the product. The material does not have to be sampled for analysis. The measurement is continuous and there is a continuous density correction for various products. But the fact that it measures hydrogen content rather than moisture content is presenting some difficulties in the universal application of this instrument for, unless the sample has a fairly constant hydrogen content, the neutron count will not give a true indication of the moisture content. Another limitation of the neutron meter lies in the fact that the neutron method does not differentiate between free water and water chemically bound in the form of hydration compounds.

IV AN INSTRUMENT FOR MEASURING MOISTURE IN CONCRETE USING CAPACITIVE TRANSDUCER

4.1 OPERATING PRINCIPLE

The operating principle of the capacitance moisture meter is based on the change occurring in the dielectric constant between its moist and dry conditions. The dielectric constant of water is very high as compared to that of concrete. Therefore, presence of a very small quantity of water in the concrete causes considerable change in the dielectric constant of the mixture of the two and it is this property of dielectric variation which has been utilised in this moisture measuring instrument. This change in dielectric constant is sensed by a capacitive transducer in terms of capacitance and is measured by using a Pseudo-bridge. The unbalanced signal caused by the change in capacitance of the transducer due to moisture is rectified and given to a dc microammeter. The microammeter reading shows a direct relationship with this change in capacitance, and hence with the moisture content in concrete upto a considerable range of moisture percentage.

4.2 DESCRIPTION OF THE INSTRUMENT

The moisture meter developed by the author have three constituent units, i.e.

- (i) Capacitive Transducer.
- (ii) Electronic Circuit.
- (iii) Indicator.

The sample is introduced into the capacitive transducer or the transducer is inserted into a prefab concrete slab so that there is concrete as dielectric between the two insulated plates forming a capacitor. The capacity change introduced by the change in moisture content of concrete is converted into a corresponding current change by the electronic unit and is indicated by the microamm-meter.

4.2.1 Capacitive Transducer^{14,15}

A capacitive transducer which converts the moisture content into the capacitance (electrical property) has been used. (fig 4.1)

The design of the sensor may be varied to suit the application. However, for this particular system the material built up on the sensor must be avoided so that it will not jeopardize the accuracy of measurement. A parallel plate capacitive transducer is constructed by using two copper clad plates ($7.5 \times 2.0 \text{ cm}^2$) separated by a 0.5 cm separation of bakelite separation. Bakelite plates have also been used to provide insulation in the inner side of the transducer. The distance between the two plates is kept small compared with the dimensions of the plates, so that the fringing effect at the edges of

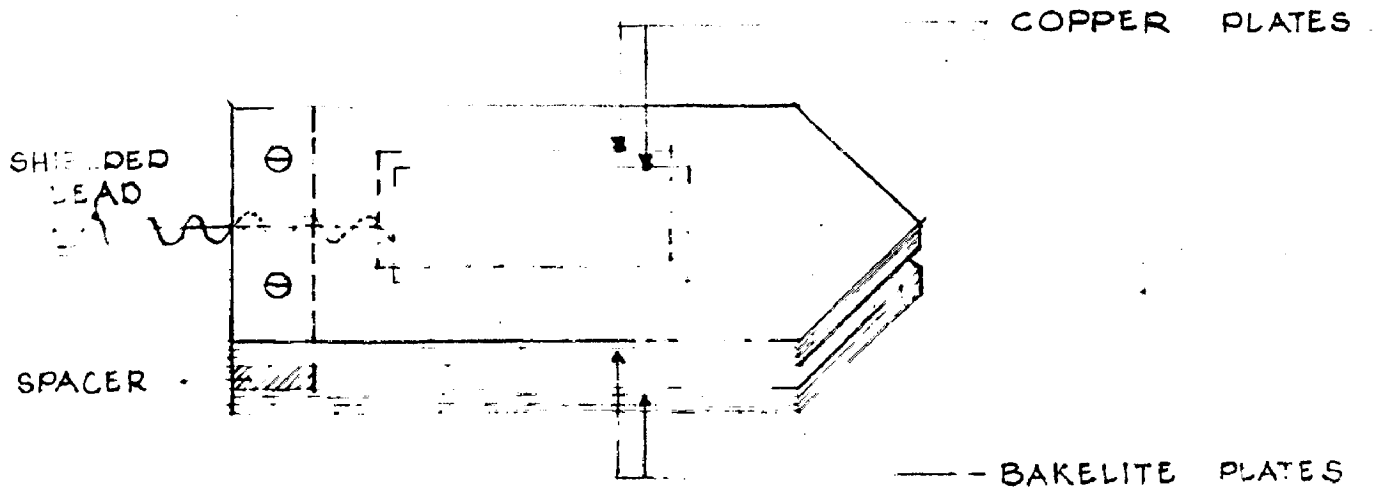


FIG. 4.1 CAPACITIVE TRANSDUCER

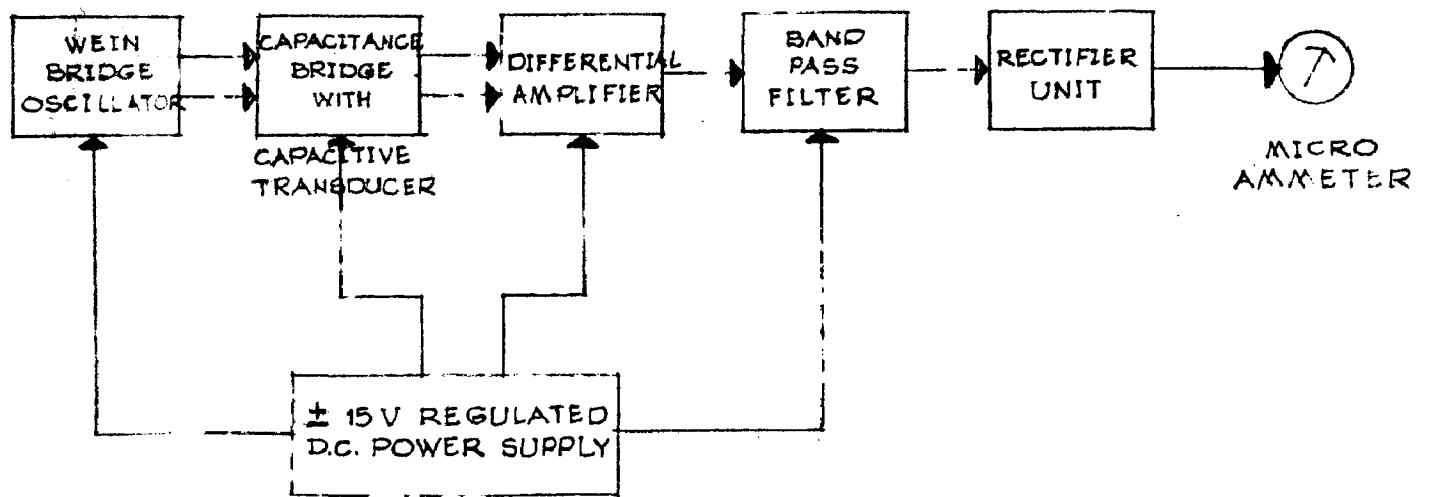


FIG. 4.2 BLOCK DIAGRAM OF THE INSTRUMENT DEVELOPED FOR THE MEASUREMENT OF MOISTURE IN CONCRETE

the plates has been neglected.

The capacitance of a parallel plate capacitor is given by

$$C = \frac{KA}{d} \quad \dots (4.1)$$

where

C = capacitance in farads

K = Dielectric constant

A = Area of one plate in meters²

d = Distance between plates in Meters

Equation (4.1) can also be written as

$$C = 0.0885 \epsilon \frac{A}{d} \quad \dots (4.2)$$

where,

C = capacitance in picofarads

ϵ = Dielectric constant of the medium between the plates.

A = Area of one plate in cm²

d = Distance between plates in cm.

In order to avoid stray capacitance effects due to the connecting leads, insulated wire has been used to connect the transducer to an arm of the bridge.

4.2.2 Electronic Circuit

(A) Block Diagram: The electronic unit consists of a regulated power supply, a Wein bridge oscillator, a pseudo bridge, a differential amplifier, in narrow band pass filter and a rectifier unit. The block diagram is shown in fig.4.2.

(1) Regulated D.C. Power Supply

A d.c. power supply of ± 15 V is required for the oscillator to generate a sinewave signal of constant and predetermined frequency and for the operational amplifiers used in the circuit. Regulated power supply is used to prevent a.c. ripples and to get a constant d.c. supply which is not affected by the change in input supply or by the change in load. A step down transformer is used to change 230 V a.c. into 30 V a.c. The two outputs from this transformer are given to two bridge rectifier circuits to get $+15$ v. and -15 V d.c. supplies.

The outputs are smoothed by two 1000 μ f capacitors.

Two feedback voltage regulators are used ^{to} get ± 15 v stabilized d.c. supply. In a feed back to voltage regulator, the d.c. output is compared continuously by the comparator with respect to a reference voltage. Any difference is amplified by the error amplifier and returned to the controlling element (Fig.4.3).

Fig.4.4 shows a series voltage regulator in which transistor Q_1 is control element and Q_2 serves as the comparator and error amplifier. Zener diode D_z provides the reference voltage. The voltage monitoring network, composed of resistors R_3 and R_4 , is adjusted by the potentiometer for the desired output voltage over the operating range of the regulator. The voltage of the monitoring network, V_4 is adjusted to

$$V_4 = \frac{V_0 R_4}{R_3 + R_4} \quad \dots \quad (4.3)$$

expression for V_4 is $V_4 = V_{BE_2} + V_R \quad \dots \quad (4.4)$

where V_R is voltage across the zener diode.

Output voltage of the regulator is given by

$$V_0 = V_R + V_{BE_2} + V_3 \quad \dots \quad (4.5)$$

$$V_3 = V_0 \frac{R_3}{R_3 + R_4} \quad \dots \quad (4.6)$$

∴

$$V_0 = V_R + V_{BE_2} + \frac{V_0 R_3}{R_3 + R_4}$$

∴

$$V_0 = (V_R + V_{BE_2}) \left(1 + \frac{R_3}{R_4} \right) \quad \dots \quad (4.7)$$

This equation shows that output voltage is essentially a function of the reference voltage and the feedback network.

A variation in potentiometer setting changes the reference level. Similarly by equation (4.4), a change in zener voltage affects the value of R_4 and V_{BE_2} , since V_{BE_2} is constant.

Examining the effect of control element on the

$$V_0 = V_1 - V_{CE_1}$$

The output varies with changes in V_{CE_1} . The value of V_{CE_1} which is given as

$$I_{B1} = I_1 - I_{C2}$$

Because I_{B1} is a function of I_{C2} , V_{CE1} and V_o vary with change in collector current of Q_2 (I_{C2}). Continuing with the same line of reasoning, we see that I_{C2} is controlled by I_{B2} . Changes in I_{B2} stem from changes in V_o , which is sensed across R_4 . We can therefore state that a change in the output voltage is transferred to, and amplified by Q_2 . The resulting change in V_{CE1} acts to return V_o to its original level.

(11) Wein Bridge Oscillator¹⁶

A constant frequency sine wave signal is required to operation the capacitance bridge.

For fixed frequency applications, the wein bridge configuration is the simplest precision sine wave generator. With an operational amplifier as a gain element, such an oscillator will have a frequency that is precisely controlled by bridge elements. Amplitude control is achieved by means of automatic gain control which is provided by Zener diode feedback. The wein bridge elements supply positive feed back around the amplifier to induce oscillation, and oscillation results at the frequency $f = \frac{1}{2\pi \sqrt{R_1 R_2 C_1 C_2}}$, where the

$$f = \frac{1}{2\pi \sqrt{R_1 R_2 C_1 C_2}}$$

positive feedback peaks. A peak in positive feedback results because the series capacitor increases feedback with frequency while the parallel capacitor decreases it. A simple Wein Bridge Oscillator is as shown in Fig.4.5. Let us assume that the output e_o is a sinusoid, then the feedback ratio of the bridge is given by

$$\beta = \frac{Z_2}{Z_1 + Z_2} = \frac{R_2}{R_1 + R_2 \left(1 + \frac{C_2}{C_1}\right) + j \left(\omega R_1 R_2 C_2 - 1/\omega C_1\right)} \quad \dots (4.8)$$

$$\text{where } Z_1 = R_1 + \frac{1}{j \omega C_1} \quad \text{and } Z_2 = \frac{R_2}{(1 + j \omega R_2 C_2)}$$

The condition for oscillation is

$$\omega_o R_1 R_2 C_2 = \frac{1}{\omega_o C_1} = 0$$

Or

$$\omega_o = \frac{1}{\sqrt{R_1 R_2 C_1 C_2}}$$

$$\text{If } R_1 = R_2 \text{ and } C_1 = C_2$$

$$\omega_o = \frac{1}{R_1 C_1} \quad \dots (4.9)$$

and from equation (4.8), $\beta = 1/3$.

Therefore, for equal resistors and capacitors in the wein bridge, the feedback factor is $1/3$. Then, for a gain of 3 through amplifier, the gain round the positive

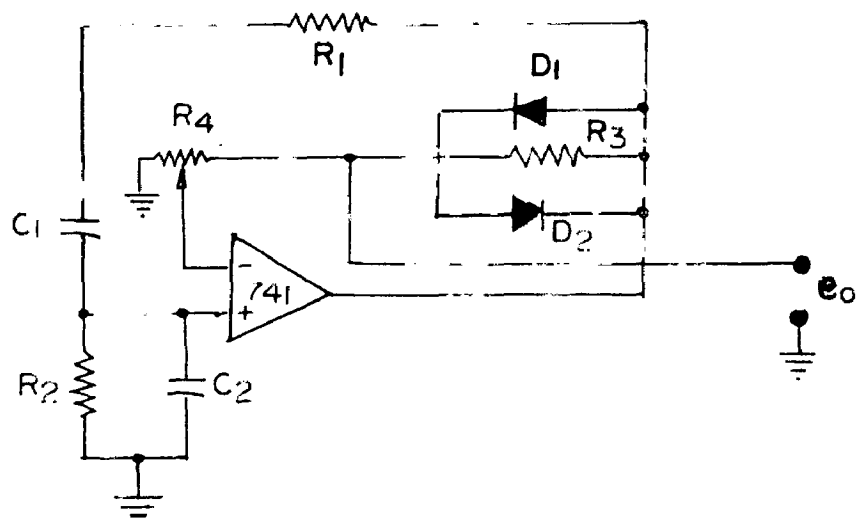


FIG.4.5 CIRCUIT DIAGRAM OF WEIN BRIDGE OSCILLATOR.

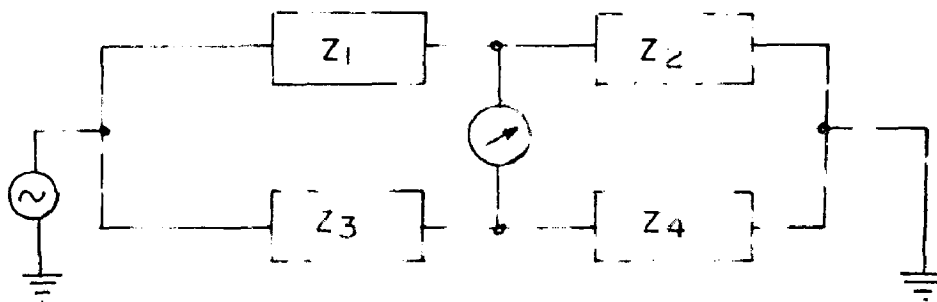


FIG.4.6 BLOCK DIAGRAM OF ORDINARY CAPACITANCE BRIDGE.

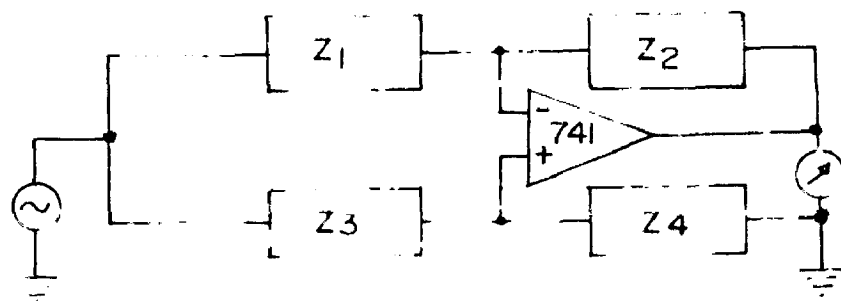


FIG.4.7 BLOCK DIAGRAM OF PSEUDO BRIDGE.

feedback loop is unity and oscillation results. The amplifier gain is set by the negative feedback. As long as the feedback factor is $1/3$, the circuit will oscillate at any preset amplitude. If $\beta < 1/3$, the oscillation amplitude will diverge with time until severe distortion occurs, and if $\beta > 1/3$, the oscillation will converge to zero with time.

The positive feedback loop has equal resistors and capacitors, while negative feedback loop has a gain of slightly greater than two. This provides β slightly greater than $1/3$, to assure oscillation. The output frequency is limited by amplifier slew rate. Slew rate of an operational amplifier is the maximum change in output per unit time that operational amplifier can deliver.

(iii) Capacitance Bridge^{17, 18}

The change in capacitance (sensed by the capacitive transducer) due to the moisture content of concrete is converted into unbalanced voltage signal by the capacitive bridge. In case of an ordinary bridge, assuming the detector is of high impedance, the transfer function is given by (Fig.4.6).

$$T = \frac{Z_2}{Z_1 + Z_2} - \frac{Z_4}{Z_3 + Z_4} \quad \dots (4.10)$$

It is well known that close to balance, the transfer

function may be considered as a linear function of the impedance responsible for the departure from balance. On the other hand, if large deviations from balance are contemplated, linear behaviour is not generally attained. However, if transfer function is rewritten as:

$$T = \frac{Z_2/Z_1}{1 + Z_2/Z_1} - \frac{Z_4/Z_3}{1 + Z_4/Z_3} \dots (4.11)$$

then it is easily seen that linearity at the detector is possible for large deviations from balance under the conditions:

$$\frac{Z_2}{Z_1} \ll 1, \quad \frac{Z_4}{Z_3} \ll 1$$

However, linearity in this case is achieved with a possible loss of sensitivity and is not generally practical.

In case of the pseudo bridge, (shown in fig.4.7) the transfer function is given as

$$T = \frac{Z_4/Z_3 - Z_2/Z_1}{1 + Z_4/Z_3} \dots (4.12)$$

if only Z_2/Z_1 is allowed to vary,

An improved bridge which compresses two similar feed back amplifier circuits has been used (Fig.4.8 and 4.9). For upper and lower circuits, the transfer functions are respectively

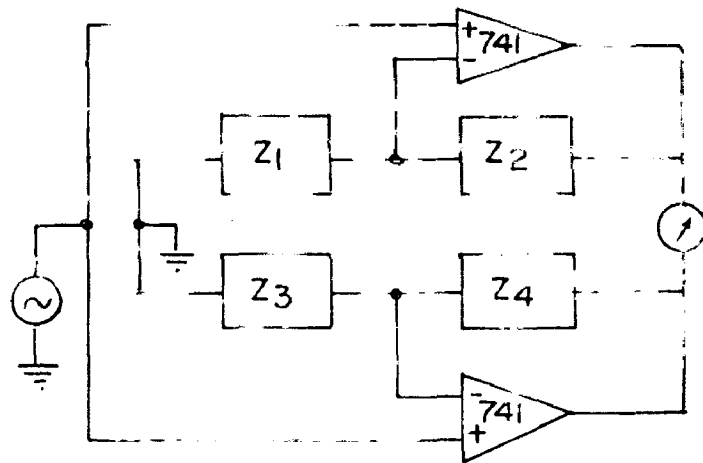


FIG.4.8 BLOCK DIAGRAM OF IMPROVED BRIDGE WITH LINEAR OUTPUT.

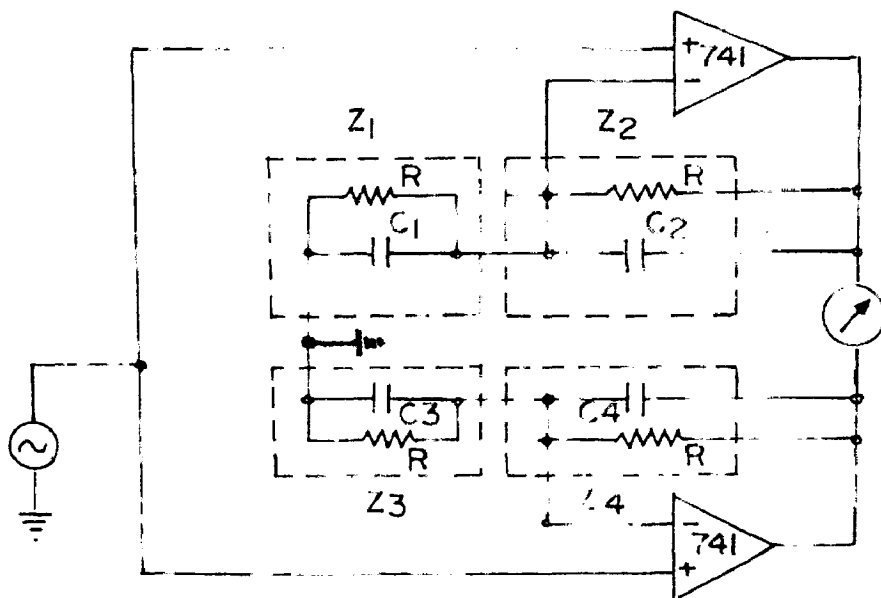


FIG.4.9 IMPLEMENTATION OF IMPROVED BRIDGE FOR CAPACITANCE MEASUREMENT.

$$T_U = \frac{Z_1 + Z_2}{Z_1} \quad , \quad T_L = \frac{Z_3 + Z_4}{Z_3}$$

Combined transfer function of the bridge is

$$T = T_U - T_L \text{ and hence}$$

$$T = \frac{Z_2}{Z_1} - \frac{Z_4}{Z_3} \quad \dots \quad (4.13)$$

If Z_1 and Z_3 are purely capacitive, and equal to $1/j\omega C_1$ and $1/j\omega C_3$ respectively, then

$$T = j\omega (Z_2 C_1 - Z_4 C_3)$$

$$\text{if } Z_2 = Z_4, \text{ then } T = j\omega Z (C_1 - C_3) \quad \dots \quad (4.14)$$

$$= Z$$

Which is simply proportional to the difference between the two oppositely varying capacitors. Due to ~~some~~ stability considerations, some high resistance is added to each side.

$$Z_2 = Z_4 \text{ and } Z_1 = \frac{1}{1/R + j\omega C_1} \quad \text{and}$$

$$Z_3 = \frac{1}{1/R + j\omega C_3}$$

Consequently,

$$T = Z \left[(1/R + j\omega C_1) - (1/R + j\omega C_3) \right]$$

$$\text{and therefore, } T = j\omega Z (C_1 - C_3)$$

which preserves the same form as equation (4.14).

(iv) Differential Amplifier¹¹

The voltage signals produced by both sides of the bridge are given to an operational amplifier as its inverting and non inverting inputs. The output of the differential amplifier is the amplified difference of the two signals i.e. a amplified unbalanced signal of the capacitance bridge.

Let us consider that the voltage difference between the inverting and non-inverting inputs of an operational amplifier is very small and assume that both inverting and non-inverting inputs are at the same voltage v_f . (Fig.4.10).

Observe that if V_2 is zero volts, the amplifier will act as inverting amplifier to V_1 . This occurs because input current of amplifier's noninverting input is zero, so no current flows through R_2 or R_f' and v_f is zero volts.

Now, if we set v_1 to be zero volts and use v_2 as an input signal, the amplifier will act like a non-inverting amplifier with a voltage divider (R_2 and R_f') supplying input voltage v_f , to the noninverting amplifier configuration.

When both V_1 and V_2 are applied simultaneously, the noninverting input causes the output to drive a voltage that will cause the voltage at the junction of R_1 and R_f to be v_f , when $v_f = V_2 \left[\frac{R_f'}{R_2 + R_f'} \right]$

instead of zero, as would occur in normal inverting amplifier.

Since the input resistance of amplifier is very high, we know

$$I_{R1} = I_{Rf} \text{ and } I_{R2} = I_{R'f}$$

$$I_{R1} = \frac{v_1 - v_f}{R_1} = I_{Rf} = \frac{v_f - v_{out}}{R_f}$$

$$\text{or } \frac{v_1 - v_f}{R_1} = \frac{v_f - v_{out}}{R_f}$$

$$\text{or } R_f v_1 - R_f v_f = R_1 v_f - R_1 v_{out}$$

$$\text{or } R_1 v_{out} = R_1 v_f + R_f v_f - R_f v_1$$

$$\text{Hence, } v_{out} = v_f \left(\frac{R_1 + R_f}{R_1} \right) - \frac{R_f}{R_1} v_1 \quad \dots(4.15)$$

This equation is for v_{out} of a noninverting amplifier with v_f as input plus the equation for v_{out} of an inverting amplifier. v_f is voltage at the junction of voltage divider R_2 and R_f with V_2 applied to R_2 , so

$$v_f = v_2 \frac{R_f'}{R_2 + R_f'}$$

Substituting this value of v_f in equation (4.15), we have,

$$v_{out} = v_2 \left(\frac{R_f'}{R_2 + R_f'} \right) \left(\frac{R_1 + R_f}{R_1} \right) - \frac{R_f}{R_1} v_1$$

If we set $R_1 = R_2$ and $R_f = R_f'$,

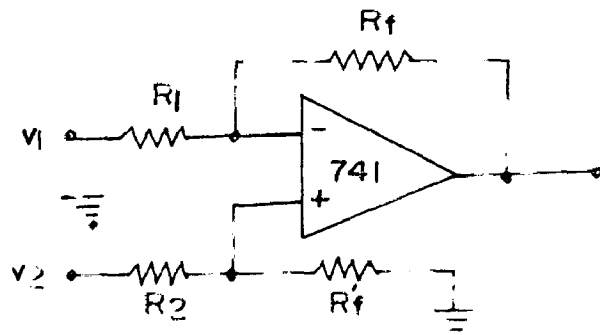


FIG.4.10 CIRCUIT DIAGRAM OF DIFFERENTIAL AMPLIFIER.

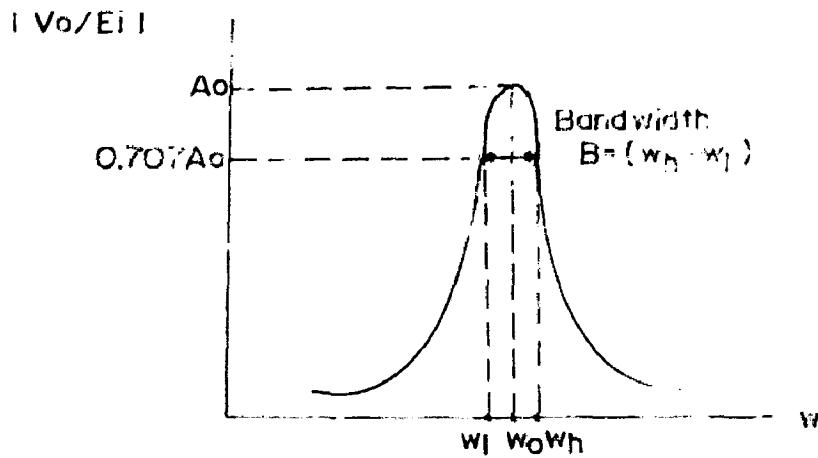


FIG.4.11 FREQUENCY RESPONSE OF BAND PASS FILTER.

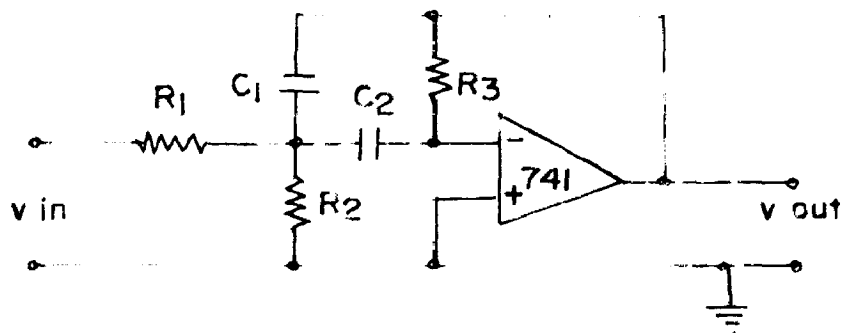


FIG.4.12 CIRCUIT DIAGRAM OF ACTIVE FILTER.

$$v_{out} = v_2 \left(\frac{R_f}{R_1 + R_f} \right) - \frac{R_f}{R_1} v_1$$

$$v_{out} = v_2 \left(\frac{R_f}{R_1} \right) - v_1 \left(\frac{R_f}{R_1} \right)$$

$$\text{and therefore, } v_{out} = \frac{R_f}{R_1} (v_2 - v_1)$$

In this situation, the output has the polarity of the larger of v_1 and v_2 .

(v) Band pass filter^{20,21}

A narrow bandpass filter is used to reject undesirable frequencies. A bandpass filter is a circuit designed to pass signals only in a certain band of frequencies while rejecting all signals outside this band. Fig.4.11 shows frequency response of a bandpass filter. This type of filter has a maximum output voltage V_{Max} or maximum voltage gain A_0 , at one frequency called the resonant frequency, ω_0 . If the frequency varies from resonance, the output voltage decreases. There is one frequency above ω_0 and one below ω_0 at which the voltage gain is $0.707 A_0$. These frequencies are designated by ω_h , the high cutoff frequency and ω_l , the low cutoff frequency. The band of frequencies between ω_h and ω_l is band width B i.e.

$$B = \omega_h - \omega_l$$

A narrow bandpass filter is one that has a bandwidth of less than one tenth of the resonant frequency ($B < 0.1 W_0$). Quality factor $Q = \frac{W}{B}$ indicates the selectivity of circuit and for narrow bandpass filters, $Q > 10$.

An active filter (Fig.4.12) has been used in the circuit which is cheaper and lighter than a passive filter at low operating frequencies, specially in audio frequency ranges, where an active filter works well. The frequency limitation of an active filter design lies in the amplifier.

(vi) Rectifier Unit²²

A device, such as the semiconductor diode, which is capable of converting a sinusoidal input waveform (whose average value is zero) into a unidirectional waveform, with a nonzero average component, is called a rectifier. Here a bridge rectifier is used to convert the a.c. unbalanced voltage into d.c. The essentials of a bridge circuit are shown as in Fig.4.13. To understand the action of this circuit, it is necessary to note that two diodes conduct simultaneously. For example, during the portion of the cycle when the transformer polarity is as shown in Fig.4.13, diodes 1 and 3 are conducting, and current passes from the positive to the negative end of the load. The conduction path is shown in figure. During the next half cycle, the transformer.

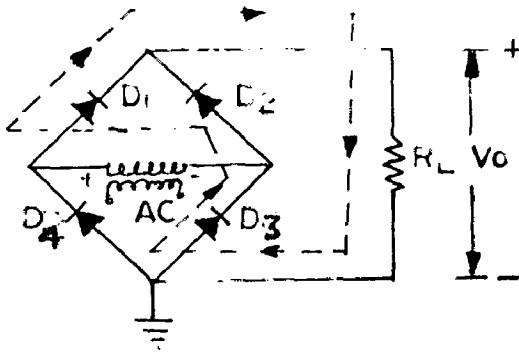


FIG.4.13 BRIDGE RECTIFIER CIRCUIT.

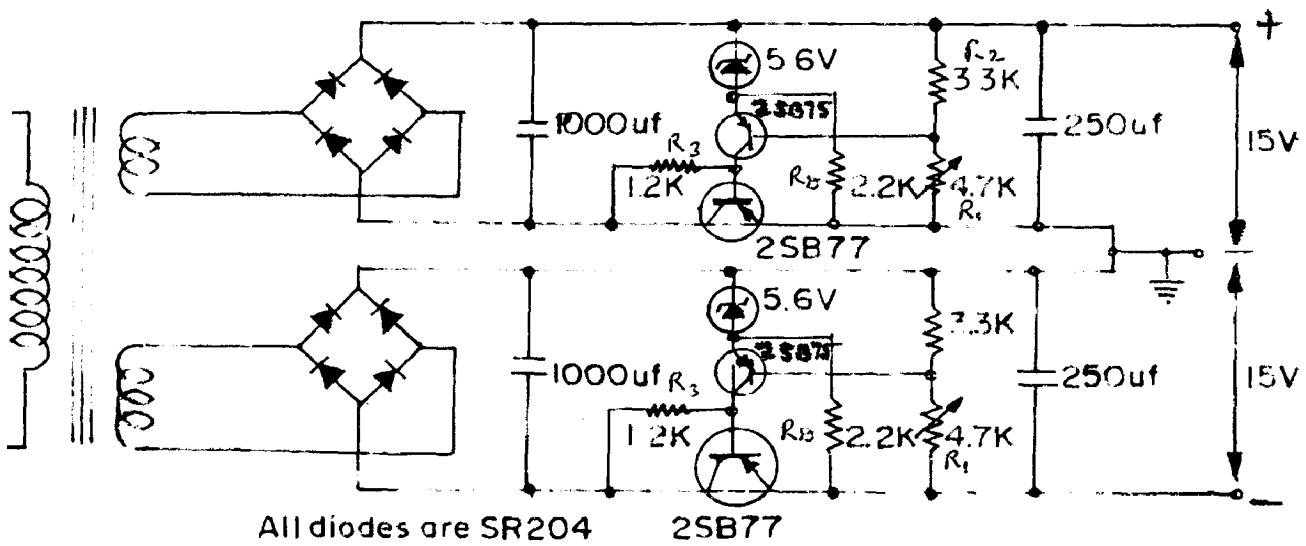


FIG.4.14 CIRCUIT DIAGRAM OF $\pm 15V$ D.C. POWER SUPPLY.

voltage reverses its polarity, and diodes 2 and 4 send current through the load in the same direction as during the previous half cycle. In case of bridge rectifier, each diode has only the voltage due to unbalance across it on the inverse cycle while in case of a full wave rectifier it is doubled.

(B) Design

(i) Regulated + 15 V D.C. Power Supply

Transformer Design

Transformer for dual power supply is designed for following specifications:

Stamping size = 15 no.

Primary Voltage = 230 (P to P)

Secondary voltage = 15V - 0-15V (P to P).

To get dual output, one primary and two separate secondary windings are being wound. Take $\mu = 1.2 \text{ Wb/m}^2$

$$E_s = 4.44 \times f \times B \times A \times N_s$$

$$30 = 4.44 \times 50 \times 1.2 \times 2.5 \times 2.5 \times 10^{-4} \times N_s$$

$$N_s = 180$$

Total number of secondary turns = 360.

$$N_p = \frac{230}{30} \times 360$$

$$= 2760$$

Maximum secondary current = 100^m A. Hence wire gauge of secondary winding = 32 SWG

$$\text{Primary current} = \frac{30}{230} \times 100 = 15 \text{ mA}$$

Hence gauge for primary winding = 38 SWG

Rectifier, filter and stabilizing Circuit

Two bridge rectifiers have been used.

Rectifier No. SR204

Two capacitors of 1000 μ f each is used for positive and negative power supplies.

Circuit diagram is as shown in Fig.4.14.

Zener voltage $V_Z = 5.6$ V

Take $I_{C_2} = 2$ mA, $I_D = 2$ mA

then $I_Z = 2 + 2 = 4$ mA

$$\therefore R_D = \frac{V_0 - V_R}{I_D} = \frac{15 - 5.6}{4 \text{ mA}} = \frac{9.4}{4 \text{ mA}} = 2.35 \text{ K}\Omega$$

$$I_{B_2} = \frac{I_{C_2}}{h_{FE_2}} = \frac{2 \text{ mA}}{30} = 2.2 \text{ K}\Omega \text{ (take)}$$

$$= 0.067 \text{ mA}$$

$$Q_1 = 2SB77$$

$$= 67 \mu\text{A}$$

$$Q_2 = 2SB75$$

$I_1 \gg I_{B_2}$, Select $I_1 = 2$ mA

$$V_{BE_2} = 0.6 \text{ V}$$

$$\text{Now, } V_2 = V_{BE_2} + V_R = 5.6 + 0.6 = 6.2 \text{ V}$$

$$R_1 = \frac{V_0 - V_2}{I_1} = \frac{15 - 6.2}{2 \text{ mA}} = \frac{8.8}{2 \text{ mA}} = 4.4 \text{ K}\Omega$$

Take $R_1 = 4.7$ K Ω preset.

$$I_{C1} = 50 \text{ mA}$$

$$\therefore I_{B1} = \frac{I_{C1} + I_1 + I_D}{h_{FE1}} = \frac{50 + 4}{30} = 1.8 \text{ mA}$$

Current through $R_3 = 2 + 1.8 = 3.8 \approx 4 \text{ mA}$

$$\therefore R_3 = \frac{V_1 - V_{BE1} - V_0}{4 \text{ mA}} = \frac{20 - 15.6}{4 \text{ mA}}$$

$$\approx \frac{4.4}{4 \text{ mA}} = 1.1 \text{ K ohm.}$$

Take $R_3 = 1.2 \text{ K Ohm.}$

Voltage drop across $R_2 = V_2 = 6.2 \text{ V}$

Therefore drop across $R_1 = 15 - 6.2 = 8.8 \text{ V}$

$$\text{Now, } \frac{R_1}{V_1} = \frac{R_2}{V_2} \text{ or } R_2 = \frac{V_2}{V_1} R_1 = \frac{6.2}{8.8} \times 4.7$$

$$= 3.3 \text{ K Ohm.}$$

Final values are:

$$Q_1 = 2SB77$$

$$Q_2 = 2SB75$$

$$R_1 = 4.7 \text{ K Ohm preset}$$

$$R_2 = 3.3 \text{ K ohm}$$

$$R_3 = 1.2 \text{ K Ohm}$$

$$R_D = 2.2 \text{ K Ohm.}$$

(ii) Main Bridge Oscillator (fig 415)

An operational amplifier 741 and two diodes are used.

When $R_1 = R_2$ and $C_1 = C_2$

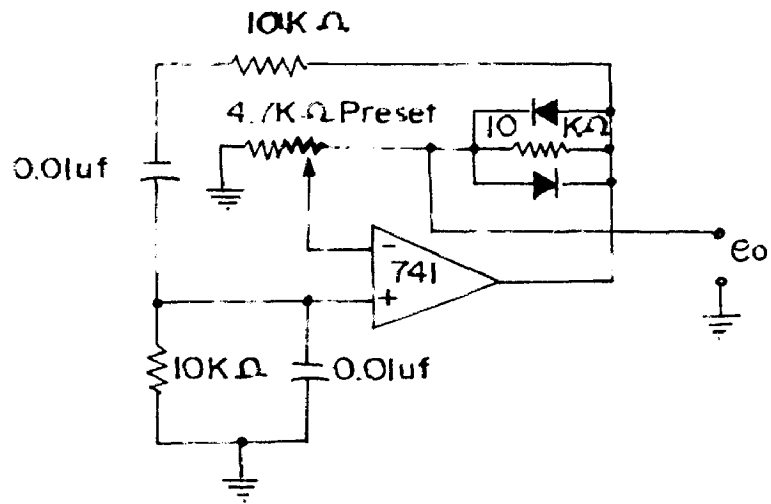


FIG.4.15 CIRCUIT DIAGRAM OF WEIN BRIDGE OSCILLATOR WITH DESIGNED COMPONENTS.

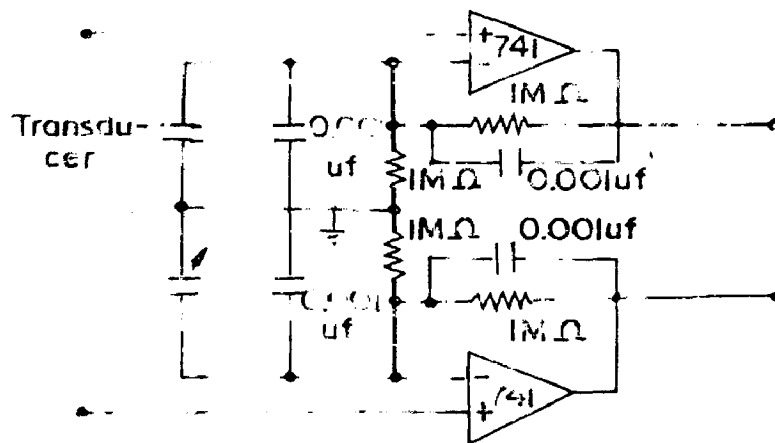


FIG.4.16 CIRCUIT DIAGRAM OF CAPACITANCE MEASURING BRIDGE WITH DESIGNED COMPONENTS.

$$f_0 = \frac{1}{2\pi R_1 C_1}$$

Taking $C_1 = C_2 = 0.01 \mu\text{f}$

$$R_1 = R_2 = 10 \text{ K Ohm.}$$

$$f_0 = \frac{1}{2\pi \times 0.01 \times 10^{-6} \times 10 \times 10^3} = \frac{10 \times 10^3}{2\pi}$$

$$f_0 = 1.59 \text{ KH}_z$$

Take $R_3 = 10 \text{ K Ohm}$ and $R_4 = 4.7 \text{ k Ohm}$ preset.

(iii) Capacitance Bridge

In the actual bridge, capacitors C_1 and C_3 are each composed of two parallel units, one of which is a fixed internal capacitor introduced to improve the stability of the system. (Take $0.001 \mu\text{f}$), while the second is the capacitance contributed by the transducer in one arm and a variable capacitor in another arm (shown in fig.4.16).

C_2 and C_4 are also taken equal to $0.001 \mu\text{f}$ each. 1M Ohm resistors are inserted in parallel in all branches. Two operational amplifiers 741 have been used.

(iv) Differential Amplifier (fig 4.17)

Take $R_1 = R_2 = 10 \text{ K Ohm}$ and to get a gain of 10,

$$R_f = R_f' = 100 \text{ K Ohm.}$$

(v) Band Pass filter

An active filter consists of resistors, and capacitors

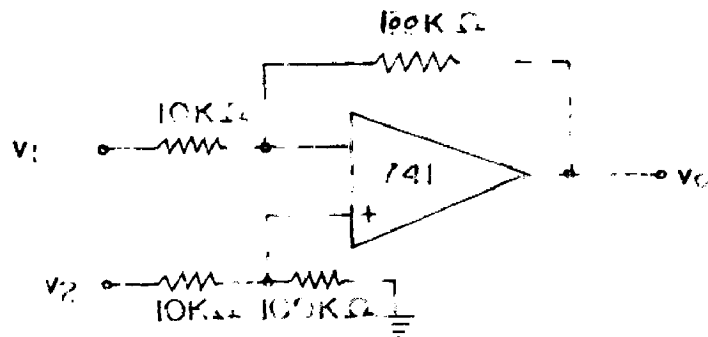


FIG.4.17 CIRCUIT DIAGRAM OF DIFFERENTIAL AMPLIFIER WITH DESIGNED COMPONENTS.

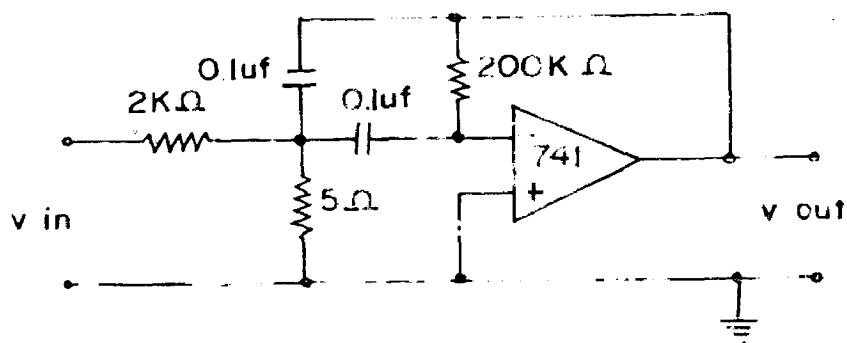


FIG.4.18 CIRCUIT DIAGRAM OF ACTIVE FILTER WITH DESIGNED COMPONENTS.

as passive elements and a high quality operational amplifier in a positive, fixed gain configuration as the active element.

$$\text{We have } \omega_0 = 10^4 \text{ rad./sec.}$$

$$\text{Bandwidth } B = 100 \text{ Hz (assume)}$$

$$\text{Quality factor } Q = \frac{10^4}{100} = 100$$

$$\text{Let Maximum gain } A_0 = 50$$

For optimum performance, it is best to make the parameters depend on resistor ratios and RC products only. This is because the temperature tracking of resistors and RC products is controllable, but variations in amplifier gain and band width are not

$$\text{Taking, } C_1 = C_2 = 0.1 \mu\text{f}$$

Now,

$$R_3 = \frac{2}{BC} = \frac{2}{100 \times 0.1 \times 10^{-6}} = 2 \times 10^5$$

$$R_3 = \underline{200 \text{ K Ohm}}$$

$$R_1 = \frac{R_3}{2 A_0} = \frac{2 \times 10^5}{2 \times 50} = 2 \times 10^3$$

$$= 2 \text{ K Ohm.}$$

$$R_2 = \frac{R_3}{4Q^2 - 2A_0} = \frac{2 \times 10^5}{4 \times 10^4 - 2 \times 50} = \frac{2 \times 10^5}{4 \times 10^4}$$

$$\approx 5 \text{ Ohm.}$$

Hence, final values are

$$C_1 = C_2 = 0.1 \mu\text{f}$$

$$R_1 = 2 \text{ K Ohm}$$

$$R_2 = 5 \text{ Ohm}$$

$$R_3 = 200 \text{ K Ohm.} \quad (\text{fig 4.18})$$

(vi) Rectifier Unit

A bridge rectifier using four diodes have been used to get d.c. value of output.

4.2.3 Indicator

The output of the bridge rectifier has been given to a d.c. microammeter through a variable resistor (47 K Ohm potentiometer) in series which gives the average value of current corresponding to the changeⁱⁿ moisture content in concrete.

The complete circuit diagram of the instrument is shown in fig.4.19.

Calibration of the Instrument

The instrument developed is first calibrated in terms of capacitance and the capacitive transducer with dry concrete as dielectric is inserted in one arm of capacitance bridge (as shown in fig.4.19). The microammeter will give some deflection because of the unbalance caused by the capacitive transducer. The bridge is balanced with the help of variable capacitor inserted in the

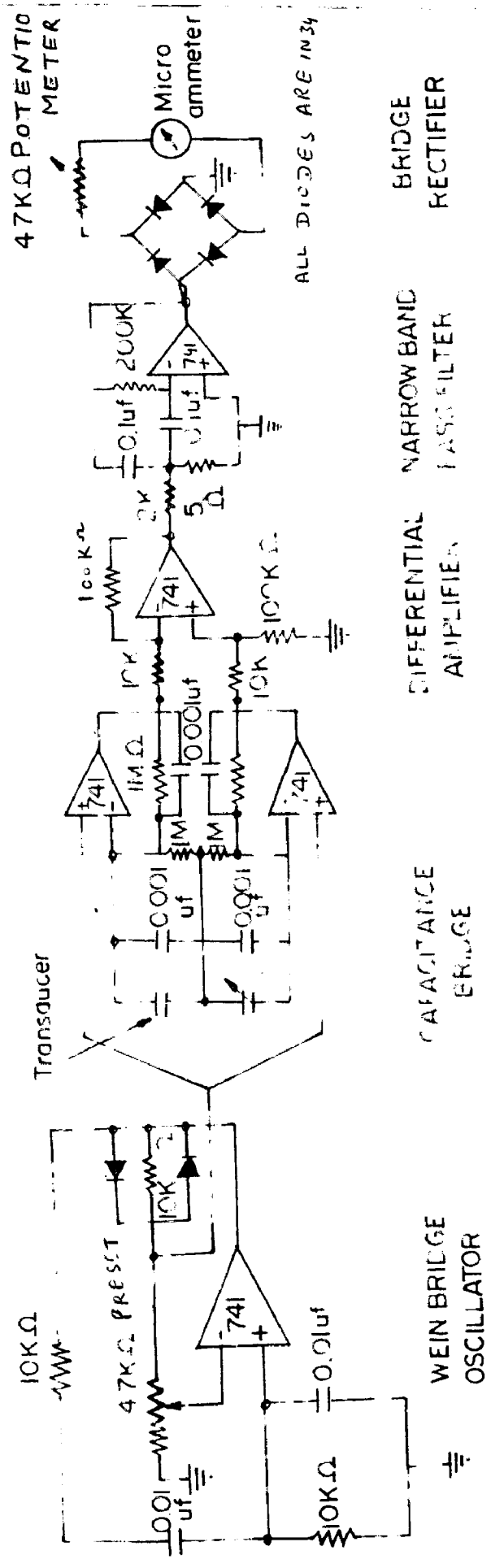


FIG. 4.19 CIRCUIT DIAGRAM OF THE MOISTURE METER.

opposite arm of the bridge. Then the calibration of the meter is done with the help of concrete samples of known moisture percentage.

4.3.1 Calibration in Terms of Capacitance

A standard variable capacitor of value $0.003 \mu\text{f}$ is inserted in one arm of the bridge in place of the transducer and full scale deflection in the micrometer is obtained. Micrometer readings were noted for different values of capacitance in descending order. (shown in Table IV).

TABLE IV

S.No.	Capacitance μf	Micrometer reading μA
1	3000	100
2	2100	700
3	1500	49
4	950	30
5	500	14

From Table IV, it is clear that there is a linear relationship between the capacitance and micrometer reading which was expected from (Fig.4.20) equation (4.14).

4.3.2 Calibration in Terms of Moisture Percentage

The capacitive transducer with concrete samples of

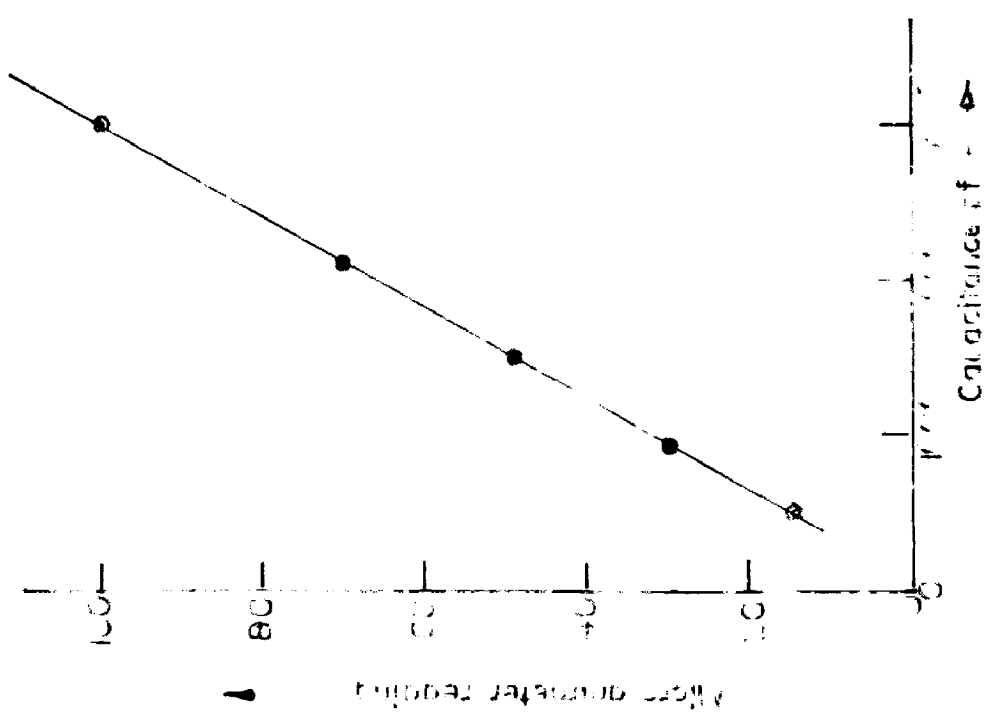


FIG. 4.20 RELATION BETWEEN CAPACITANCE & MICRO AMMETER READING.

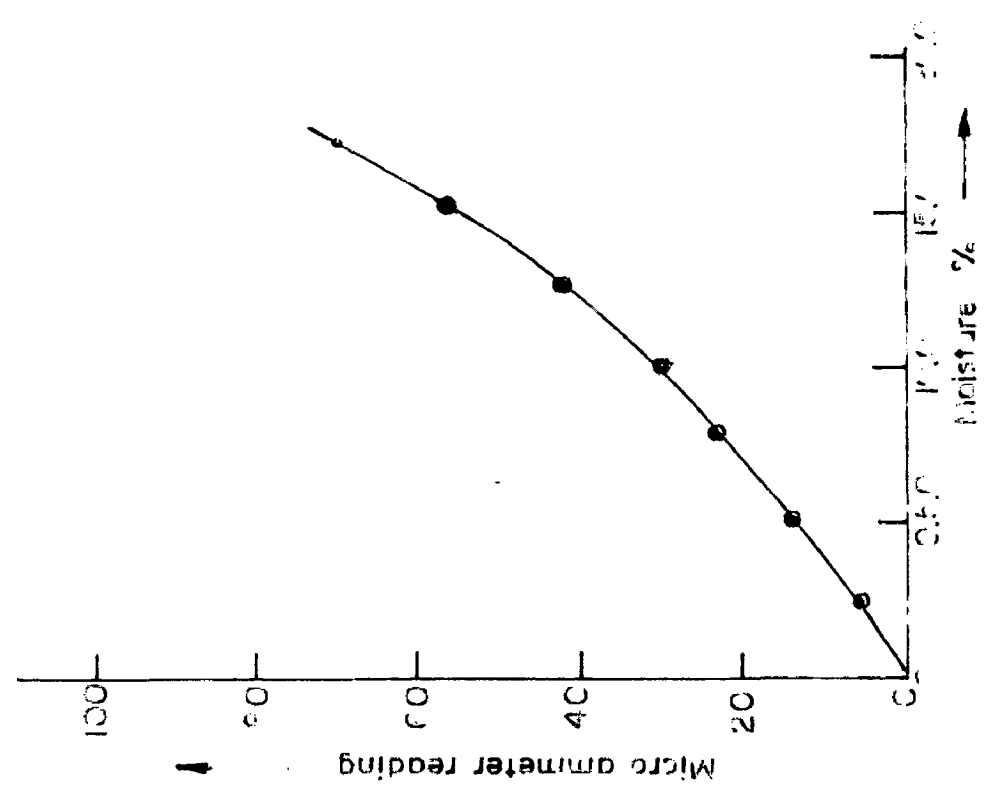


FIG. 4.21 RELATION BETWEEN MOISTURE % IN CONCRETE & MICRO AMMETER READING.

various known moisture percentages was inserted in one arm of the bridge and the readings of microammeter were noted as shown in Table V.

TABLE V

S.No.	Moisture Content %	Microammeter Readings μ A
1	2.5	6.0
2	5.0	14.0
3	7.5	22.0
4	10.0	30.0
5	12.5	42.0
6	15.0	56.0
7	17.5	70.0

Fig.4.21 shows that there is approximately a linear relationship between the moisture percentage in concrete and the microammeter readings.

4.4 MERITS AND DEMERITS OF THE MOISTURE METER

4.41 Merits

The instrument developed for the measurement of moisture in concrete has the following merits:

- (1) The moisture meter is simple, compact and portable.
- (2) Capacitive transducer has been used as sensor which is simple in construction and has the advantage that the physical mechanism involved in its action does not

depend upon the physical properties of the material.

(3) The major advantage of this moisture meter is that the presence of electrolytes, salts or acids in the sample does not effect the reading of microammeter.

(4) An appreciable change in dielectric constant occurs for small changes of moisture content in a concrete sample and hence a good sensitivity has been achieved.

(5) The use of an improved capacitance bridge with operational amplifiers and high resistances makes it more stable.

(6) Stray capacitances are neglected by having a common ground terminal and ^{shielded} insulated wire for connecting the transducer.

(7) This instrument gives instantaneous reading and hence moisture can be controlled in a processing condition.

(8) The instrument is cheaper than the other available moisture meters.

4.4.2 Demerits

(1) Error may arise from humidity affecting the insulation resistance and from stray electric field inducing parasitic potentials in the not grounded plate.

(2) One serious draw back with the transducer is that the level of material in transducer should be same.

Otherwise wrong results will be obtained.

(3) Transducer has to be cleaned for each sample in order to *avoid* the coating of hard scale which effects the capacitance due to dielectric change of medium resulting in an erroneous moisture content indication.

CONCLUSIONS

In this dissertation the author has attempted to describe about all the existing methods of moisture measurement in concrete. The main problem in most of the methods seems to be is that the variable property to be measured is also affected by factors other than moisture.

The instrument developed by the author can be used for continuous as well as intermittent measurement of moisture content in concrete. It can also be used to measure the moisture at different points in case of a big concrete slab. This moisture meter can also measure moisture content in other loose materials like sand, soils, etc., floor etc. But it has to be calibrated again for each material.

The performance of the instrument has been found satisfactory. The sensitivity of the moisture meter is approximately 0.1% moisture per microampere. It has been found that there exists an approximately linear relation between the moisture percentage and microammeter readings. The deviation of the curve from linearity is due to the unbalance of phase and packing density and a better performance of the instrument can be obtained by providing a phase balancing facility. The phase changes should be made without influencing the relative amplitudes of the signals on both sides of the bridge.

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