Some aspects of the mechanical testing of hot rolled asphalt surfacings.

CHOYCE, P. W.

SOME ASPECTS OF THE MECHANICAL TESTING OF HOT ROLLED ASPHALT SURFACINGS.

BY

P.W. CHOYCE BSc. M.I.H.E

Thesis submitted to the Council for National Academic Awards for the Degree of Master of Philosophy based on research conducted in the Department of Civil Engineering, Sheffield City Polytechnic in collaboration with the ESSO Petroleum Company Ltd.

OCTOBER 1981.

ABSTRACT

Hot Rolled Asphalt Wearing course mixtures, containing up to 55% by mass of coarse aggregate, were tested over a range of binder contents using the following test methods:-

Marshall Test
Indirect-Tensile Test
Wheel-Tracking Test.

The results obtained were used to assess the ability of each of these methods to

(i) assist in the selection of an optimum mixture composition, from the point of view of resistance to deformation

(ii) predict the resistance to deformation of the various mixtures tested.

It was found that the results obtained by all three test methods could be used to define an "optimum binder content" for a given set of constituents, and that both Marshall Stability and Marshall Quotient were closely related to resistance to deformation, as measured in the Wheel-Tracking Test.

In the light of the results obtained, the Marshall Test would appear to be most suitable of the three (from the practical point of view) for application to the design of Hot Rolled Asphalt Mixtures.

However, before total confidence can be placed in the results obtained by this method, there are several improvements which must be made.

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ACKNOWLEDGEMENTS

The author wishes to extend his special thanks to:

The ESSO Petroleum Company Limited, in collaboration with whom, this work was carried out.

Dr. I. F. Taylor (Sheffield City Polytechnic) and Mr. K. A. Lammiman (ESSO Petroleum Co. Ltd., now retired), for their assistance during the course of the work, in their roles as Academic and Industrial Supervisors, respectively and
Mr. A. P. Morton, for the invaluable assistance and support given during the course of the laboratory work.

In addition, thanks are due to the following people, who were of great assistance throughout the work.

Mr. A. Thompson
Mr. P. F. Lonsborough
Mr. S. Wilson
Mr. K. Wells
Mr. J. Holding, all of Sheffield City Polytechnic

Dr. F. D. Harper
Mr. D. M. Giles
Mr. C. M. Mitchell
Mr. M. Dixon
Mr. A. J. Suart, all of the ESSO Petroleum Co. Ltd.

and also

Mr. F. A. Jacobs (Transport and Road Research Laboratory)

Last, but not least, the author wishes to thank Lesley Furness, whose efforts in typing this thesis are very much appreciated.

NOTATION

W_M	Total mass of mix
W_{ST}	Mass of coarse aggregate in mix
W_{SF}	Mass of fine aggregate and filler in mix
W_S	Mass of fine aggregate in mix
W_F	Mass of filler in mix
W_B	Mass of binder in mix
w_1	% by mass, coarse aggregate in mix (stone content)
w_2	% by mass, fine aggregate in mix
w_3	% by mass, filler in mix
w_B	% by mass, binder in mix (binder content)
S_1	Relative density of coarse aggregate
S_2	Relative density of fine aggregate
S_3	Relative density of filler
S_B	Relative density of binder
FR	% filler retained on 75 micron sieve
CR	% fine aggregate retained on 75 micron sieve
SR	% fine aggregate retained on 2.36 mm sieve

S_M	Relative Mix Density (g/ml)
S_A	Compacted Aggregate Density (g/ml)
V_M	Percentage Voids in Mix
V_A	Percentage Voids in the Mineral Aggregate
V_F	Percentage Voids Filled with Binder
B	Specimen Volume (ml)
H	Specimen Height (mm)
S	Marshall Stability (kN)
F	Marshall Flow (mm)
Q	Marshall Quotient (kN/mm)

I.T.S.	Indirect Tensile Strength ($N/mm^2 \times 10^{-1}$)
T	Tensile Quotient (N/mm^2)
D	Vertical Deformation at Failure (mm)
T.R.	Wheel-Tracking Rate (mm/hr)
$R.D._{100}$	Rut Depth after 100 passes (mm)
$R.D._{1000}$	Rut Depth after 1000 passes (mm)
$R.D._{END}$	Rut Depth after 45 minutes (mm)

Note to Reader

Throughout the investigation, values of S_M, S_A, V_M, V_A, V_F and B have been determined in accordance with B.S. 594 (1973).

To maintain consistency with this Standard, the units of S_M and S_A are quoted as g/ml (equivalent to g/cm^3) and likewise those for B as ml (equivalent to cm^3).

Further, units of g/ml are quoted for S_M, even though B.S. 594 refers to it as "Relative" Mix Density. (A term which would normally carry no units).

1. INTRODUCTION

Hot Rolled Asphalt (H.R.A.) (1) (2) is a dense, impervious, gap-graded material. Its composition is based upon a sand-filler-binder mortar, comprising between 35 and 100% by mass of the mixture depending upon the application, the remainder of the mixture being a relatively single-sized coarse aggregate.

As a wearing course material H.R.A. has secured itself a pre-eminent position in the U.K. for the surfacing of flexible construction for motorways, trunk and principal roads.(3) (4) The most widely used composition for this purpose is a low-stone content mixture containing 30% by mass coarse aggregate, with a fine natural sand, limestone dust as filler and a fairly high content of 50 penetration grade bitumen.(5) It is usually laid to a thickness of 40mm and a skid resistant surface is provided by the application of coated chippings.

The H.R.A. mixtures used today have developed out of experience gained over a number of years. The first examples being laid on the Kings Road, Chelsea and Pelham Street, Kensington in 1895.(6) Shortly after this, an American Clifford Richardson came to England and helped in the development and production of H.R.A. on a scientific basis. As soon as sufficient experience and data had been gained the then British Engineering Standards Association in collaboration with the Ministry of Transport and others were able to draw up British Standard specifications related to the use of H.R.A. These were issued in 1928, B.S. 342 and B.S. 344 covered respectively, the use of two course and single course H.R.A. When revision of these Standards became necessary they were combined and the number changed to the more familiar B.S. 594. This was first issued in 1935 and since that time further revisions have been made in 1945, 1950, 1958, 1961 and most recently in 1973. The only major changes over the years have been the continued increase in the hardness of binder used for heavily-trafficked roads and a reduction in the number of stone contents specified.

The composition of H.R.A. mixtures has in the past been specified in terms of "recipes", the percent by mass of each constituent being listed in table form. The present edition of B.S. 594(7) includes recipe specifications for wearing course mixtures containing up to 55% by mass of coarse aggregate. For each coarse aggregate content three binder content schedules are given, ranging from lean to rich relatively speaking. Guidance on selection of the appropriate schedule is given in the Standard, and is based upon traffic intensity and geographical location. A typical B.S. 594 recipe specification for wearing course mixtures is given in table 1.

The recipe method of specification has a number of advantages in terms of the ease with which a material can be specified, manufactured within given tolerances and be tested for compliance with the original specification. Over the years H.R.A. produced in accordance with such specifications has proven itself capable of providing an adequate and durable surfacing material under heavy traffic conditions. This success is attributed to its tolerance to composition variation, its flexibility, fatigue resistance,(8) crack resistance(9) and to its workability

TABLE 1

COMPOSITION OF WEARING COURSE MIXTURES - ROCK AGGREGATE (RECIPE METHOD)

Schedule No.	Percentage By Mass Of Total Mixture		
	Coarse Aggregate retained on 2.36mm test sieve	Soluble Binder	Aggregate passing 75µm B.S. test sieve
1A	0	10.3	13.0
	15	9.1	11.0
	30	7.9	8.9
	40	7.1	7.5
	55	5.9	5.4
1B	0	10.8	14.0
	15	9.6	12.0
	30	8.4	9.9
	40	7.6	8.5
	55	6.4	6.4
1C	0	11.3	15.0
	15	10.1	13.0
	30	8.9	10.9
	40	8.1	9.5
	55	6.8	7.4

and ease with which it can be compacted to form a dense, impermeable layer. The moderate U.K. climate has also contributed to this success.

However, since the early 1960's problems with H.R.A. recipe mixtures have become apparent. In certain parts of the U.K. the locally available aggregates were not producing completely satisfactory mixtures for use on heavily trafficked roads and motorways. Particularly at severe sites, notably steep gradients where heavy traffic was slow and canalized, marked permanent deformation was occurring and producing ruts in the wheel tracks. A typical example of this is described by Windmill,(10) while Please(11) reports that marked deformation had occurred in Schedule 1 H.R.A.'s on a straight section of dual-carriageway after only three years trafficking.

The formation of such ruts has adverse effects upon the riding quality and safety of the surfacing and causes further canalization of traffic which serves to worsen the situation. The deformation which is evident at the road surface may result from the accumulation of deformations of all the pavement layers, plus deformation of the underlying subgrade. The latter is not usually a problem in the U.K., where adequate pavement design(4) ensures, by the provision of adequate layer thickness, that subgrade deformations are negligible. The problem in the U.K. is, therefore, associated with deformations confined to the pavement layers, and in particular, the uppermost surfacing layers.(12) Such deformations occur due to, firstly some compaction of the mixture by traffic, and secondly, by the accumulation of permanent deformations. When H.R.A. deforms due to the passage of a wheel, part of the deformation is recovered immediately, part recovers after some delay and a small amount is irrecoverable, permanent deformation.(13) It is the accumulation of such permanent deformations over a period of time which is the major cause of rutting. The deformation behaviour described previously is not only influenced by the intrinsic properties of the mixture but also by certain external factors, in particular, traffic loading and climatic conditions.(14)

In the U.K. during the 1960's and 1970's a rapid growth in the number and weight of commercial vehicles using major roads occurred(15) and this was a major factor contributing to the appearance of the deformation problems and its continued presence. More recently the exceptionally hot summers of 1975 and 1976(16) served to accelerate the occurrence and severity of the problem.

The appearance of such a problem in H.R.A. mixtures which had performed adequately in the past, served to highlight certain limitations of the recipe method of specification. Firstly, the permitted tolerances for constituent proportions, and in particular the binder content, had in the past been used by manufacturers to make adjustments within the permitted range to produce a mixture with properties most suited to a particular application, based on past experience. With a growing emphasis on achieving compliance with specification, this margin for adjustment was no longer available to manufacturers, who now found it necessary to aim for the mid-point of the specification, which in some cases resulted in the production of an inferior material.

Secondly, although the specification makes certain requirements regarding the properties of the constituents, there are differences in specific gravity, grading, particle shape and surface texture which have a marked effect upon the properties of the resulting mixture. Please(11) indicates that this is particularly true for the sand fraction, for 30% stone H.R.A. wearing course mixtures at a fixed mid-specification binder content of 7.9% by mass, resistance to deformation as measured in the laboratory can vary by a factor of 10 depending upon the type of sand used. In addition, the use of asphaltic cements of the same penetration grade but different rheological properties can also affect resistance to deformation by the same degree.
In the practical situation this variation could be even greater when additional factors such as hardening of the binder during mixing and differences in coarse aggregate and filler are considered.

Indications are that recipe type specifications fail to take proper account of the properties and binder requirement of the actual constituents used, and may also unduly limit materials permitted for use. Also, the associated materials selection, testing and quality control has become centred upon achieving compliance with specifications rather than getting the best performance from the available materials. The resulting mixtures when laid on the road could have variable engineering properties and a tendency to rut under heavy traffic, particularly at severe sites.

By the end of the 1960's there was, therefore, a need for H.R.A. surfacing mixtures with an increased resistance to deformation under heavy traffic. One of the possible solutions available to achieve this end was the adoption of a Mix Design technique, based upon a Mechanical testing procedure. Mix Design can be considered in simple terms as the selection of constituent proportions with the aid of results obtained from a Mechanical test. Such a procedure may or may not include design criteria related to traffic intensity and climatic conditions. Provided a suitable test procedure could be adopted, benefits should be gained from, in particular, the selection of the appropriate binder content for the constituents used, enabling the production of mixtures of optimum composition as regards performance. Successful application of such a design method, may also make it possible to design adequate mixtures, using materials at present excluded by the specification, thus enabling the best use to be made of locally available aggregates.

In December, 1973 an extensive revision of B.S. 594(7) was issued which included for the first time a Mix Design procedure based upon a Mechanical test. This section was at this stage an optional alternative to the recipe method of specification for H.R.A. wearing course mixtures. The Mechanical test procedure upon which this design method was based, was the Marshall test. This method of testing had previously been used extensively abroad and in particular in the U.S.A.(17) Its use had in the past been confined to Asphaltic Concrete(18) and had for some years been used in the U.K. in connection with airfield pavements(19) constructed with this material. The present mix design procedure detailed in B.S. 594,(7) requires the selection of an optimum binder content for the sand-filler-binder mortar, based on results obtained in the Marshall test. An adjustment is then applied in order to obtain a target binder content for the total mixture, coarse aggregate included.

Since the introduction of the optional mix design procedure, results from full scale road trials, laboratory investigations and feedback from industry has furnished information regarding the performance of designed mixtures, and has allowed re-appraisal of the procedure. As a result, additional specification clauses for H.R.A. wearing course mixtures(20) (21) were issued in February, 1979. The introduction of these clauses made the use of the Mix Design procedure compulsory for all surfacing and resurfacing work on trunk roads and motorways, with effect from 1st, April, 1980, and also included, amongst others, a requirement for mortar stability at its optimum binder content, depending upon traffic flow. The collection of information in the manner indicated previously will continue and further updating of the procedure will take place as it becomes necessary.

This then is the current position regarding H.R.A. Mix Design in British practise, at present B.S. 594 is undergoing a further major revision which is due to be published in the near future. It is expected that the revised Standard will contain fairly extensive changes and additions to the Mix Design procedure and associated design criteria. The extension of the Design procedure in a reliable form to the total mixture, coarse aggregate included, and a statement of Design criteria in terms of the total mixture would seem the next logical step.(22)

It is hoped that the work carried out within the scope of the present investigation will lead to an increased understanding of the mechanical properties of H.R.A. mixtures, and the interrelationship thereof. Further, the results obtained should also throw light on the ability of certain mechanical tests to assist in the design of mixtures having improved mechanical properties.

2. BACKGROUND INFORMATION

2.1 The Mechanical Testing of Bituminous Paving Mixtures

2.1.1 Introduction:

The following sections review in general terms the application of Mechanical testing procedures to Bituminous Paving mixtures with an emphasis on those used to assess resistance to deformation.

Since the early part of this century many such procedures have been developed in many countries, notably the U.S.A. When considering the wide diversity of the available methods, it is convenient to make a distinction, based upon the nature of the test itself, and regard these methods as being either

Empirical methods,
Fundamental methods
or Simulative methods.

2.1.2 Empirical Test Methods:

2.1.2.1 General

An Empirical test is one in which some arbitrary property of a compacted paving mixture is determined, typically the maximum load sustained under given loading conditions. Such test methods now form the basis of many widely used Mix Design procedures in which test results are considered along with the density and void content of compacted specimens, in order to select a mixture composition which will perform adequately from the point of view of resistance to deformation and durability, yielding a mixture with:

(i) Sufficient binder to ensure durability.

(ii) Sufficient stability to withstand traffic loading without undue distortion.

(iii) Sufficient air voids to allow for slight additional compaction under traffic without bleeding or loss of stability, yet low enough to exclude air and moisture.

(iv) Sufficient workability to permit easy placement and compaction to the required density.

In most cases an "optimum binder content" for a given aggregate gradation is selected and is used directly or acts as a guide to the binder content to be used in practise.

In such tests, it is the arbitrary property measured which is used to assess a mixture's resistance to deformation under traffic, often termed "stability". This property is not a measure of any intrinsic mixture property, it is, therefore, essential that a correlation between laboratory and road performance be established. This done, it is then possible to define design criteria in terms of laboratory parameters, to be applied depending upon traffic and climatic conditions.

2.1.2.2 Common Empirical Test Methods

Marshall test(1)(7)(17)(23)

Hveem Stabilometer and Cohesiometer test(1)(17)(24)

Hubbard - Field test(1)(17)(25)(26)

Duriez test.(14)(27)

2.1.2.3 Advantages of Empirical Test Methods

(i) Equipment and procedures are usually simple.

(ii) Can be carried out quickly, allowing a large number of compositions to be assessed quickly.

(iii) Provided they are used within the constraints of proven laboratory - road correlations, adequate, economic mixtures can be produced.

(iv) Their simplicity and speed of operation means they can easily be adopted for on-site quality control.

2.1.2.4 Disadvantages of Empirical Test Methods

(i) It is necessary to establish a correlation between laboratory and road performance before results can be of any practical use.

(ii) Many tests are only applicable to a limited range of mixture types and well defined conditions of traffic and climate.

(iii) Results obtained with different Empirical methods do not agree with each other to any great extent.

(iv) Loading conditions often bear no resemblance to those found in practise.

(v) In most cases it is not possible to analyse the stresses acting during testing.

2.1.3 Fundamental Test Methods:

2.1.3.1 General

A Fundamental test sets out to measure some intrinsic (fundamental) property of the mixture under test. Unlike Empirical methods, they are, with certain exceptions, unsuitable for Mix Design applications and tend, therefore, to be considered as research tools.

Certain tests of this type were designed specifically for the determination of those properties which would allow the problem of resistance to deformation to be tackled from a more theoretical (rational) approach. Others developed more recently allow the determination of those properties required for computer programs used in multi-layer elastic (viscoelastic) methods of pavement design.

2.1.3.2 Common Fundamental Test Methods:

Triaxial test(1)(28)(29)(30)(31)
Unconfined Compression test(1)(32)
Indirect-Tensile test(33)(34)
Uniaxial Creep test(35)(36)(37)
Various repeated loading tests:
    Dynamic Modulus test(35)(39)(40)
    Fatigue test(38)(40)
    Dynamic Creep test.(38)

2.1.3.3 Advantages of Fundamental Test Methods:

(i) Loading systems employed permit the calculation of stresses acting during testing.

(ii) Stresses more closely resembling those found in practise can be reproduced.

(iii) Results obtained permit a more theoretical approach to the problem of resistance to deformation, and a computer-aided approach to Pavement Design.

2.1.3.4 Disadvantages of Fundamental Test Methods:

(i) Testing equipment is usually complex, expensive and requires trained operatives.

(ii) Time required for testing is often considerable.

(iii) Most procedures are not suited to Mix Design in the sense described previously and, therefore, usage is mainly confined to research rather than practical applications.

2.1.4 Simulative Test Methods:

2.1.4.1 General

Test methods referred to previously are considered to have 2 major drawbacks. Firstly, in many cases the loading conditions and the stresses produced within the specimen fail to simulate the practical situation. Secondly, even if it is possible to reproduce such conditions, difficulties arise when trying to apply results obtained for test specimens to the behaviour of the same mixtures in a layered pavement system.

As the name suggests, simulative tests set out to overcome such shortcomings by attempting to simulate the conditions experienced in the practical road situation.

2.1.4.2 Common Simulative Test Methods:

Laboratory Wheel-Tracking test(1)(42)(43)
Miniature Test Tracks(44)(45)(46)
Large-Scale Test Tracks(46)(47)
Full Scale Road Trials.(46)(48)(49)

2.1.4.3 Advantages of Simulative Test Methods:

(i) Simulate to varying degrees, the loading conditions, stresses, compaction, environment and layered structure found in practise.

(ii) Allow assessment of resistance to deformation under realistic conditions, thereby allowing mixtures to be "ranked" more realistically than by other methods.

(iii) Large-scale test tracks permit the behaviour of mixtures under controlled traffic conditions to be investigated.

(iv) Full-Scale Road Trials allow the behaviour of mixtures under real environmental and traffic conditions to be observed.

2.1.4.4 Disadvantages of Simulative Test Methods:

(i) They are in general more expensive to construct and operate than "conventional" test methods.

(ii) Require more time to carry out and in the case of Large-Scale test tracks and Full-Scale Road Trials this time can be prohibitive.

(iii) In Full-Scale Road Trials and Large-Scale test tracks, environmental factors are variable.

(iv) Results from Laboratory Wheel-Tracking tests and Miniature test tracks need to be correlated with actual road performance before the results are of practical use.

(v) Such methods cannot reasonably be applied to Mix Design in the conventional sense.

2.2 Test Methods Used in the Current Investigation:

2.2.1 Introduction:

The following sections refer in detail to various aspects of the test methods used in the current investigation. These methods are namely:

Marshall test

Indirect-Tensile test

and Wheel-Tracking test.

It should be noted that many of the previous applications have not been directly related to H.R.A., however, in order to draw upon the experience gained with other materials, the author felt it necessary to report upon applications to Bituminous mixtures in general; with specific reference to H.R.A. whenever possible.

2.2.2 The Marshall Test Method:

2.2.2.1 Outline of Test Method

Mixtures are made up at several binder contents and cylindrical specimens 101.6 mm dia x approx 63.5 mm high (4 in dia x 2.5 in) are compacted in steel moulds using a standard drop-hammer. (See later).

Determinations are then made to facilitate the calculation of the density and void content of specimens.

The Marshall test itself is a type of compression test, conducted at 60°C (140°F). Load is applied to the curved surface of the specimen at a constant rate of strain of 50.8 mm/min (2 in/min), and the maximum load sustained along with the deformation at maximum load are recorded as Marshall Stability (N, lbf or kgf) and

Marshall Flow (mm or 0.01 in) respectively.

From the results obtained, an "optimum binder content" is determined, the manner in which this is done depends upon the type of mix and its application.
N.B. A more detailed description can be found elsewhere.(7)(17)(23)

2.2.2.2 Historical Background:

The Marshall test procedure was originally developed in America by Bruce Marshall of the Mississippi State Highways Department.

During the 1940's, the U.S. Corps of Engineers adopted this method of testing and developed around it the Marshall Mix Design procedure, variations on which are widely used today. The work carried out to this end was two-fold:
(i) the development of a compaction procedure, which resulted in specimen densities equivalent to those of pavement cores,(50)
(ii) the establishment of suitable design criteria for selection of "optimum binder content", based on the results from the trafficking of a Full-Scale Test Track at the U.S. Waterways Experimental Stations, Vicksburg, Mississippi.(51)

The results from the above led to the adoption of the drop-hammer method of compaction and the design criteria set down in table 2. Optimum binder content (O.B.C.) being based upon the mean of the binder contents corresponding to the following in the laboratory test:
(i) Maximum Stability.
(ii) Maximum Mix Density.
(iii) A value of Voids in the Mix at the middle of the specified

range.

(iv) A value of Voids filled with Binder at the middle of the specified range.

N.B. A check is then made to ensure all criteria, including Flow, are met at this O.B.C.

This procedure for Mixture design is applicable to Asphaltic Concrete with a nominal maximum aggregate size of 25 mm (1 in) or less, for the surfacing of airfield pavements, and forms part of an overall Pavement Design procedure.(52)

Over the years this original method has been extended to the design of asphaltic concrete surfacings for Highway pavements. Currently the most widely used method for this purpose is the Asphalt Institute method,(17) based on design criteria somewhat different to those specified for airfields, see table 2. Besides prominent use in the U.S.A., the Marshall method has found worldwide acceptance for the design of dense, continuously graded asphaltic concrete type surfacings for Highway pavements, see table 3.

Table 2

Marshall Design Criteria : Asphaltic Concrete (Surfacings)

U.S. Corps of Engineers - AIRFIELDS

Stability	All mixtures	500 lb min (2220N)
Flow	All mixtures	20 (0.01 in) max (5.1 mm)
Voids in Mix	Asphaltic Concrete Sand Asphalt	3 - 5% 5 - 7%
Voids Filled with Binder	Asphaltic Concrete Sand Asphalt	75 - 85% 65 - 75%

Asphalt Institute(17) - HIGHWAYS

TRAFFIC CATEGORY	HEAVY	MEDIUM	LIGHT	
Blows per face	75	50	35	
Stability (min)	750 (3340)	500 (2220)	500 (2220)	lbs N
Flow (min - max)	8 - 16 (2.0 - 4.1)	8 - 18 (2.0 - 4.6)	8 - 20 (2.0 - 5.1)	0.01 in mm
Voids in Mix (min - max)	3 - 5	3 - 5	3 - 5	%
Voids in Mineral Aggregate	Minimum value given in design manual depending on nominal maximum size of aggregate.			

U.K. - AIRFIELDS(19)

Stability	1800 lb (min) (8000N)
Flow	0 - 16 (0.01 in) (4.1 mm)
Voids in Mix	3 - 4%
Voids filled with Binder	76 - 82%

Table 3

International Marshall Requirements for Heavily Trafficked Roads

(after Akcroyd et al(53)).

Country	Blows per face	Stability (min) (kN)	Flow (mm)	Quotient (kN/mm)	Voids in Mix(%)	Void in mineral aggregate (%)
France	50	8.0	1.0-3.0	-	4 max	-
Germany	75	3.0	1.0-4.0	-	1-4	-
Italy	75	8.0	1.0-3.5	-	3-6	-
Holland	50	5.5	2.5-4.5	3.0*	2-4	-
Spain	75	7.5	2.0-3.5	1.5-2.0	3-5	15-22
Switzerland	50	10.0	1.8-2.2	-	2-4	-
Turkey	50	6.0	2.5-4.5	-	3-5	12*
U.S.A.	75	5.0	2.0-4.5	-	3-5	15*
Canada	75	5.4	2.0-5.0	-	2-5	14-15
Japan	75	6.0	2.0-4.0	-	3-5	17-20
South Africa	75	4.5	2.0-4.0	1.5*	2-10	15*

* Minimum values.

In the U.K., use has been limited to the design of airfield surfacings,(19) with design criteria based on those originally developed being used, see table 2. Until recently its application to Highway surfacings had been limited to a few experimental sections of asphaltic concrete.(54)(55)

2.2.2.3 Application to Hot Rolled Asphalt

The Marshall test was included in B.S. 594 (1973),(7) as an optional alternative to the recipe method of specification for H.R.A. wearing course mixtures. This was the first application of a Mix Design method to H.R.A. in the U.K. and the reasons for the selection of the Marshall test for this purpose would appear to stem from a combination of the following:

(i) Simplicity of apparatus and procedure.
(ii) Worldwide acceptance of this method, for the design of other dense bituminous surfacings, and the associated knowledge gained from this.
(iii) Availability of equipment and trained personnel in many U.K. laboratories.

As early as 1958, Broome and Please(56) reported on an investigation to determine the usefulness of Mechanical tests in the design of H.R.A. surfacings, in which the Marshall test was one of 8 tests considered. Since then, interest in the Marshall test appears to have grown, in 1961, Please(57) discussed its value in assisting in the design of H.R.A. wearing course mixtures, and its ability to measure the resistance to deformation of such mixtures.

Some time later, a joint Transport and Road Research Laboratory -

Asphalt and Coated Macadam Association (T.R.R.L. - A.C.M.A.) Working Party(58) was set up to investigate in greater detail the application of the Marshall test to H.R.A. mix design. This took the form of an inter-laboratory study, in which 6 laboratories, using the draft test procedure, proposed for the future (1973) revision of B.S. 594, investigated the properties of H.R.A. mixtures comprised of 8 different fine aggregate sands covering a wide range of physical properties. The results of this investigation furnished information regarding the range of O.B.C.(59) and Marshall Stability(59) which could be expected for "typical" sands available in the U.K., and the degree of repeatability and reproducibility of test results.(58)

The correlation of laboratory results and field performance is an essential part of design procedures based on Empirical tests, and to this end, Full Scale Road Trials have been laid(11)(59)(60) on sections of heavily trafficked roads in the U.K. Most important of these was that laid on the A.33 Winchester-by-pass(59) in 1972 which incorporated 30% stone H.R.A. mixtures comprised of the 8 sands investigated previously. Although periodically monitored, no information regarding the performance of the mixtures under traffic has yet been published.

The optional Mix Design procedure introduced in 1973(7) entails the determination of an optimum binder content for the sand-filler-binder portion of the mix, coarse aggregate is not included. Test specimens, 24 in all, 2 at each of 12 binder contents, at 0.5% by mass increments are compacted (50 blows per face) and tested as previously described. Using the data obtained the following parameters are plotted vs. binder content:

Mix density (S_M).

Compacted Aggregate density (S_A)

Marshall Stability (S)

The O.B.C. is taken as the mean of the 3 binder contents corresponding to the maximum values of S_M, S_A and S, an adjustment is then made to obtain a Target binder content for a mixture containing S% coarse aggregate.

N.B. No limiting values, regarding Stability, Flow or Void Content were included at this time.

In the years following 1973, feedback from industry, continued monitoring of Full-Scale Road Trials and further laboratory work secured data for re-appraisal of the original design procedure. On the basis of this in February, 1979 the issue of Departmental Standard HD/2/79,(20) revised parts of the specification(3) for H.R.A. wearing courses. This document made the use of the design method compulsory for the surfacing and resurfacing of all trunk roads, principal roads and motorways, carrying over 250 commercial vehicles in one direction per day, and introduced the requirements shown in table 4 regarding the properties of the sand-filler-binder mortar at O.B.C.

Table 4:

Requirements for H.R.A. Wearing Course Mixtures

(design method) after HD/2/79(20)

(a) Optimum binder content of sand-filler-binder mortar - not less than 9.2% by mass.

(b) Stability:

Traffic Flow (Commercial Vehicles per day)	Minimum Stability at mortar O.B.C. (Newtons)
Less than 2000	3000
2000 - 4000	4500
4000 - 6000	5500
More than 6000	6500

(c) Flow: not greater than 5 mm at mortar O.B.C.

Further, the design method was extended to cover mixtures containing Crushed Rock Fine aggregate and Heavy-Duty bitumen,(61) in an attempt to gain further improvements in mixture performance.

This then is the present situation in the U.K., elsewhere, mixtures resembling H.R.A. are used in certain European countries(14) and South Africa.(62)(63) Those used in South Africa have in the past been based on B.S. 594 compositions but more recently a trend towards the use of the Marshall test to design such mixtures is apparent. Board(64) reports the use of this method to design 30% H.R.A. mixtures, based on past experience, the designed mixtures are required to have the following properties to ensure satisfactory performance:

Minimum Stability	3330 N
Flow	2.0 - 4.6 mm
Voids in Mix	4 - 6 %

Later, in 1974, Marais(65) puts forward tentative design criteria for H.R.A. mixtures, and these are included in table 3.

2.2.2.4 Effect of Sand Fraction on Binder Requirement and Asphalt Properties

Different sands although conforming to B.S. 594 grading limits require differing amounts of binder in order to produce the most stable and durable mix. This results directly from differences in the physical properties of the sands, namely

Particle-size distribution (grading)
Particle shape
Surface texture.

These influence the packing characteristics and in particular the voids in the compacted aggregate and hence the amount of binder which can be held by the mix.(66)

For sand-filler-binder mixtures Price(67) and Duthie(66) concluded that grading was the major factor governing the binder contents required to produce maximum mix density and max stability. Particle shape and surface texture were also important but had a lesser influence. Hence, applying the Marshall test over a range of binder contents, should permit the determination of an optimum binder content, giving the best compromise between durability and strength.

Particle shape, surface texture and to a lesser extent grading also influence the value of maximum stability(66)(67) attained by a given mix, as a result of their effect on internal friction and particle interlock. In the light of the requirements of HD/2/79,(21) emphasis has shifted to the selection of rough/angular sands in order to produce high stability mixes, here again the Marshall test is of use in assessing which sands are suitable for the severest traffic conditions.

To illustrate the effect of grading on the properties of the resulting mix, attention is drawn to table 5. Showing the effect on binder content for maximum stability and the value of maximum stability, of altering the grading of a single sand, within the limits of B.S. 594.

Table 5:

Effect of Grading on Marshall Properties:
(Based on the work of Bellamy(68))

Grading / Property	Coarse-end B.S. 594	Mid-point B.S. 594	Fine-end B.S. 594
Binder Content for Maximum Stability (% by mass)	7.0	8.0	11.0
Maximum Stability (Newtons)	5775	4485	3100

The preceding has related to sand-filler-binder mixtures.

As far as 30% stone H.R.A. are concerned, results presented by Duthie(60) and Lees(69) indicate the sand fraction is still dominant in determining the binder requirement and properties of the mix, confirming similar findings for Asphaltic Concrete.(70)

2.2.2.5 Repeatability and Reproducibility:

For a test method to be satisfactorily applied to Mix Design, the results obtained must be repeatable and reproducible. These terms are defined elsewhere(71) and refer to the degree of variation associated with the execution of the test procedure.

Numerous authors(72)(73)(74)(75)(76)(77) have reported considerable variation in measured Stability values for what are nominally identical samples of Asphaltic Concrete. Quantified in terms of Standard Deviation(73) results included in table 6a indicate values ranging 550 - 1670N (100 - 300 lbs.) In considering these results it must be recognised that although they refer to single operators using single sets of apparatus, mixtures were sampled from operational mixing plant, thereby introducing sources of variation not related to test method alone.(73)

In a controlled laboratory investigation in 1962, Vokac(78) determines a value of 340N (61 lbs) for Standard Deviation. However, the validity of this result must be questioned as the standard drop-hammer compactor was not used and this is considered by some(76) to be one of the major sources of the variation associated with this test.

The preceding relates to the variation occuring when the Marshall test is repeated in a single laboratory (repeatability). Results concerning the variation occuring when the test is carried out in different laboratories (reproducibility) are given in table 6(b).

Table 6:

Marshall Test : Repeatability and Reproducibility

(a) Plant Studies - Asphaltic Concrete

Source of Data	Standard Deviation - Stability lbs	 Newtons
Odasz and Nafus(72) 1954	255	1400
Corbett and Warden(73) 1955	132 - 264	720 - 1450
Corbett(74) 1956	140 - 195	770 - 1075
Parker(75) 1956	275 - 301	1500 - 1650
Nevitt(76) 1959	199	1100
Shook(77) 1960	155	850

(b) Laboratory Studies - Hot Rolled Asphalt
(after Hills(58))

Results are mean values for mixtures containing 8 different sands, tested in 6 different laboratories.
MORTAR MIXES - properties at OBC.

	Reproducibility (R)	R%
Stability (kN)	2.3	47
Flow (mm)	1.5	36
Quotient (kN/mm)	0.7	57

30% Stone Mixes - properties at OBC.

Stability (kN)	2.8	36
Flow (mm)	1.1	36
Quotient (kN/mm)	1.6	61

N.B. Reproducibility (R) = Standard deviation x 2.77

$$R\% = \frac{R}{\text{mean}} \times 100$$

These figures were obtained in the TRRL - ACMA study referred to previously,(58) and are in close agreement with results obtained in an extensive investigation of a similar nature carried out in Holland,(79) and those presented by Hingley.(80)

From the available information, it is apparent that at present the repeatability and reproducibility of the Marshall test are unacceptable.

2.2.2.6 What is Measured in the Marshall Test?

In the literature the Marshall test is variously described as a "type of unconfined compression test" or a "type of semi-confined compression test." Due to the nature of the loading conditions it is impossible to analyse the stress conditions during the test(81) and it is also concluded that a certain degree of lateral confinement is imposed upon the specimen due to friction forces.(82) The presence of confinement means that the test is not equivalent to an unconfined compression test on tall specimens,(83) however, an equivalent degree of confinement can be produced in unconfined compression tests on specimens with low, height-diameter ratios.(84)

Hence, when talking in terms of Marshall Stability we are essentially considering a measure of shear-strength under conditions of limited frictional (lateral) support, the latter increasing as Stability increases.(69) Under such conditions the mixture under test relies to a large extent upon Cohesion to develop its strength.

Marshall Flow on the other hand is simply a measure of permanent strain at failure, resistance to such strain being obtained primarily from aggregate interlock and internal friction. McLeod,(85) points to a strong negative correlation in the results of Goetz,(78) between

Marshall Flow and Angle of Internal Friction which is seen by Lees(69) to imply that Flow is directly related to the geometry of the original aggregate structure. In comparing Flow with Hveem Relative Stability,(24) Please(57) shows a similar relationship exists for HRA's and concludes that assigning a maximum limit to Flow is equivalent to assigning a minimum limit to Internal Friction.

2.2.2.7 Ability to Assess Resistance to Deformation

The ability of Marshall Stability or Flow values to predict a mixture's resistance to deformation under traffic, appears to be lacking in many instances.(42)(44)(81)

Early work with H.R.A.(56) indicated that these values alone were not able to accurately predict a mixture's performance in all cases. A "ranking" of mixtures in terms of Stability and Flow, differed somewhat from that on the basis of their performance in simulative tests. A similar disagreement is reported elsewhere.(86)

In the road situation and in simulative tests, mixtures are restrained by the surrounding and underlying material, although the magnitude of restraint may differ, in such instances resistance to deformation will be largely a function of aggregate interlock and internal friction, rather than cohesion as in the Marshall test. This fact may in some way account for the poor agreement observed.(69)

To overcome the limitations of Stability or Flow alone, many authors(35)(57)(87) suggest that the use of the ratio of Stability to Flow, referred to as Marshall Quotient (Q), may lead to a better correlation with performance.

This ratio was first proposed by Nijboer(88) who equated the Stiffness Modulus of a mixture, under conditions of the Marshall test to

$$= 1.58 \frac{S}{F} \ (\text{kg/cm}^2)$$

where S = Marshall Stability (kg)

F = Marshall Flow (mm)

and S/F = Marshall Quotient (Q) = (kg/mm).

Attempts were then made to set required values of Q, initially

$$\underset{(\text{kg/mm})}{\text{Required } Q} \geq 30 \times \underset{(\text{kg/cm}^2)}{\text{Tyre pressure}}$$

with Edwards(89) later reporting that other work suggested figures of Q as

1.0 kN/mm for Northern Europe

2.0 kN/mm for areas with hotter climates.

Such requirements are now part of specifications in certain countries,(14)(53) see table 3. This is not the case in the U.K., although it is reported(58) that certain Highway Authorities specify their own requirements regarding Q, typical values suggested as suitable for heavy traffic conditions are:

Sand-filler-binder mix	1.1 to 1.5 kN/mm(58)
Stone-filled mix	2.0 to 2.5 kN/mm.(90)

In this context, consideration of the requirements of HD/2/79(27) can lead to what may be termed "implied" minimum values of Q, for different traffic intensities, see table 7.

Table 7:

Marshall Quotient - "implied values" HD/2/79

Sand-filler-binder mixes at O.B.C.

Traffic Category c.v.d.	Specified Minimum Stability (kN)	Implied Minimum Quotient* (kN/mm)
less than 2000	3.0	0.6
2000 - 4000	4.5	0.9
4000 - 6000	5.5	1.1
more than 6000	6.5	1.3

*maximum Flow value at O.B.C. = 5 mm

hence "implied" Q = Stability ÷ 5.0, kN/mm.

Although Marshall Quotient should correlate better with resistance to deformation,(57) results of laboratory studies(91)(92) using simulative test methods fail to indicate definitely if this is the case.

However, results of laboratory-road correlations do suggest that the relationship between rut depth under traffic is more closely related to Quotient(14)(43)(50) than Stability, with the odd exception.(93) Lack of such information stems from the time needed to collect it and those relationships which have been established show a high degree of scatter, which can be attributed to:

(i) the variable environmental and traffic conditions

(ii) poor repeatability/reproducibility of the test

(iii) use of rut depths after only short periods under traffic.

In conclusion, it appears both Stability and Quotient are closely related to the performance of H.R.A. mixtures. More data is required before any great significance can be placed on results.

2.2.2.8 Applications to Quality Control:

In common with all manufacturing processes the production of Bituminous mixtures is subject to variation.(73) As mixtures of the highest quality are required this variation must be kept to a minimum, the techniques employed to this end are termed Quality Control.

The Marshall test has been used for many years in the U.S.A.(72)(73)(77) and elsewhere(94) as the basis for Quality Control of Asphaltic concrete. This entails testing samples of mixture taken from the mixing plant, and plotting the test results on Statistical Quality Control Charts,(77) the mathematical basis of which is described elsewhere.(95) Failure of data to fall within predetermined limits indicates variation is greater than expected, and the source of this variation can be sought and rectified within a short time,(72) thus maintaining a high quality product (mixture).

In the U.K., H.R.A. mixtures have in the past been tested, only to check compliance with the recipe specification. With an increasing emphasis on deformation resistant mixtures certain Highway Authorities(90)(96) have begun to employ techniques similar to those outlined above, which are applicable either at the point of manufacture or can be extended to a central laboratory.(90)

2.2.3 The Indirect-Tensile Test Method

2.2.3.1 Outline of Test Method

This involves applying an increasing compressive load, distributed along opposite generators of a cylindrical specimen resulting in the development of a relatively uniform tensile stress acting perpendicular to the loaded diametral plane. Failure usually occurs by "splitting" along this plane due to the tensile stress, thereby allowing calculation of the Tensile Strength, knowing the load at failure(P) and specimen diameter(D) and length(L).

2.2.3.2 Theory

The theoretical stress distribution, (see figure 1) under such loading conditions can be derived from Frocht's equations for stresses at a point(97) for the case of a thin disc subjected to point loads at opposite ends of a diameter. (Corresponding to a cylinder with line loads along opposite generators). This indicates that on the loaded diameter:

(i) Vertical stress is compressive, varying from $\frac{6P}{\pi LD}$ at the centre to infinity beneath the load points.

(ii) Horizontal stress is tensile, with a constant value of $\frac{2P}{\pi LD}$ - (1)

Under such conditions the specimen would be expected to fail in compression directly beneath the load points, however, in reality conditions deviate considerably from those assumed in the exact solution given above:

(i) The heterogeneous nature and non-linear stress-strain behaviour of materials under test will undoubtedly effect

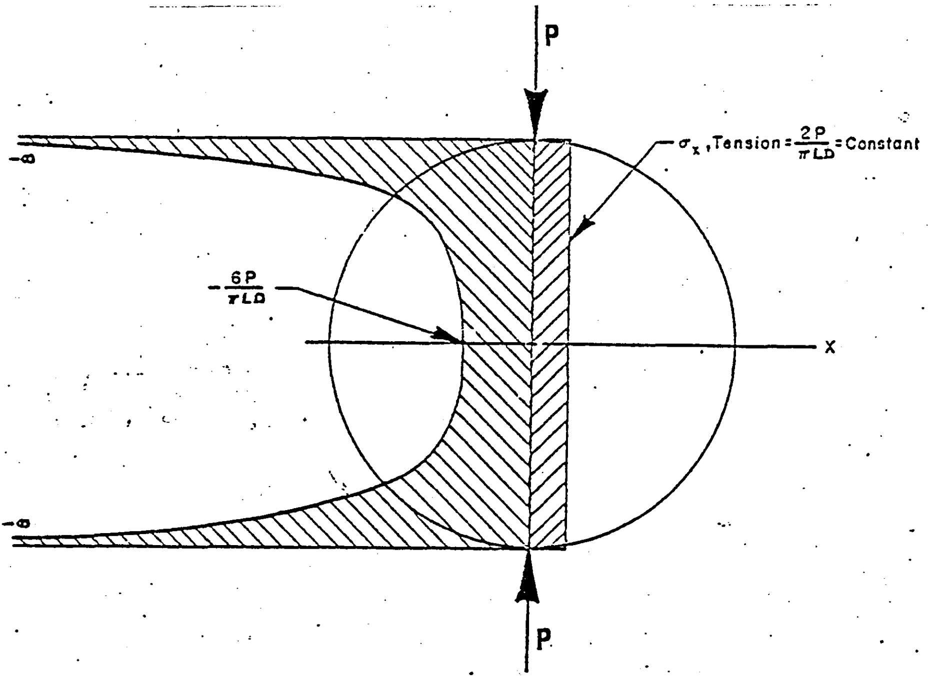
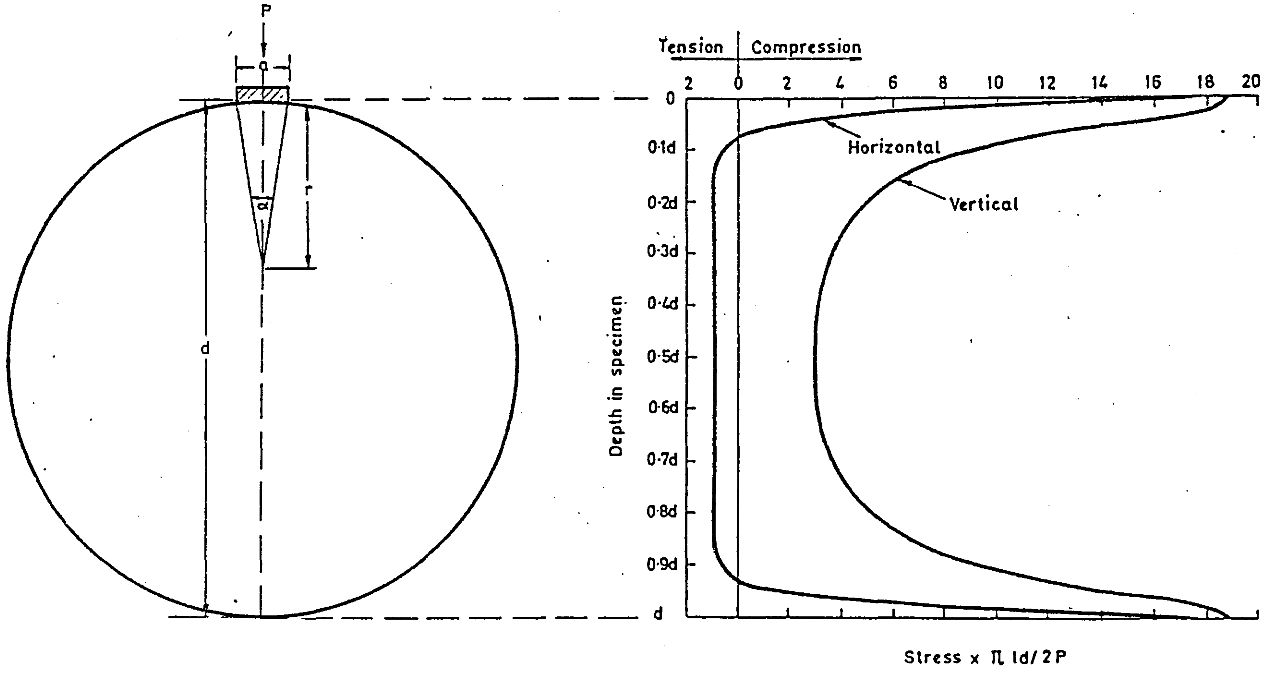


FIG.1 STRESS DISTRIBUTION IN A CYLINDER DUE TO LINE LOAD



Applied load, P, distributed over width 'a'

Distribution of horizontal and vertical stresses on the vertical diameter of a cylinder loaded over a width $a = \frac{d}{12}$

Fig.2. STRESS DISTRIBUTION IN A CYLINDER DUE TO A DISTRIBUTED LOAD

the stress distribution to an unknown degree. Wright(98) concludes this effect is probably small and that the non-linear stress-strain behaviour will tend to relieve the more highly stressed areas, resulting in 'high' values of Tensile strength.

(ii) Load is unavoidably distributed over a finite area and Wright(98) concludes that this results in: (refer figure 2)

(a) a significant reduction in vertical compressive stress directly beneath the loaded area.

(b) a change in the horizontal tensile stress, to compression beneath the applied load, whilst remaining constant over approximately ¾ of the vertical diameter, at a value of

$$\frac{2P}{\pi LD} \quad 1 - \frac{d}{2a}(\alpha - \sin\alpha) \qquad - (2)$$

Again, failure in compression beneath the applied load would be expected, however, it is suggested(98)(99) that in this region a triaxial stress situation exists and stresses much greater than the compressive strength can develop without causing failure. Failure in compression does not, therefore, occur before the tensile failure.

The value of Tensile Strength, given by equation (2) differs by less than 0.5% from that given by Frocht's formula (1), and the latter is, therefore, sufficient to evaluate Tensile Strength.(99) In general there is little reason to doubt the results obtained provided the specimen fails in tension.(97)

2.2.3.3 Historical Background

The Indirect-Tensile test is reported(100) to have been developed simultaneously and independently by Akazawa in Japan and Carneiro and Barcellos in Brazil, circa 1942. Due to the latter being the generally acknowledged origin, this test is commonly referred to as the Brazilian test.

Since its development, it has been successfully applied to a range of "brittle" materials, notably concrete. Its use has been favoured by many as it is much easier to conduct than other so-called direct methods of Tensile Strength determination.(97)

Application to Bituminous materials has been limited until recently, those attempts which have been made are now discussed.

2.2.3.4 Application to Bituminous Mixtures

The earliest application(101) to Asphaltic Concrete was in 1962, using prismatic specimens and a method of analysis based on the Mohr-Coulomb Strength Law. The stress at failure was related to Cohesion and Angle of Internal Friction, later used to calculate Bearing Capacity.

Later work in the U.S.A.(39)(102) and Canada(103) utilised this method to evaluate the resistance of Asphaltic Concrete to tensile cracking at low temperatures(102)(103) and tensile strength at high temperatures.(39)

In 1965, a major investigation into the application of the Indirect-Tensile test to Stabilised and Asphalt-treated materials was begun at the University of Texas, at Austin.(97) This included a theoretical and experimental evaluation of its application to Asphaltic Concrete(97)(104) and later an extension of the theory,(105) method and analysis(34) to enable the determination of Young's Modulus and Poisson's Ratio.(106)(107) These techniques were successfully applied, to determine factors influencing the Tensile properties of Asphalt-treated materials(108)(109) and to correlate Tensile properties with Stabilometer and Cohesiometer values.(110)(111) More recently, the procedures have been modified further to facilitate the determination of the properties of such materials under repeated loading,(112)(113) with a tentative American Society for Testing Materials (A.S.T.M.) standard being prepared.(114)

Elsewhere, Maupin(115) and Marias(65) have attempted to relate values of Tensile "stiffness" and Indirect-Tensile strength to the fatigue life of bituminous mixtures.

In Belgium,(14) this method has been used extensively since the early 1970's. Huet(33) describes the test method, including the measurement of Vertical Deformation at failure (ΔD), enabling the calculation of:

$$\text{Vertical Diametral Strain at Failure} = \frac{\Delta D}{D}$$

$$\text{and Tensile Coefficient under Diametral Compression at Failure} = \frac{P}{L.\Delta D} \quad \text{(units of stress)}$$

Huet(33) indicates that the latter is a function of temperature and suggests this may, therefore, give an indication of a mixture's resistance to deformation at high temperatures, while results obtained at -10°C will indicate a mixture resistance to cracking at low temperatures. Results from an inter-laboratory investigation indicate that the repeatability and reproducibility of the test are good,(33) but its ability to assess the effect of compositional variation claimed by Huet(33) is not supported by Célard.(116)

In July, 1973, the Belgian Roads Administration introduced for a trial period, tentative "Stability" criteria for Asphaltic Concrete, based upon Indirect-Tensile test results,(14) these are shown in table 8.

Table 8

Tentative "Design Criteria based on Indirect-Tensile test."

(Belgium)

Test Temperature Property	-10°C	45°C
$\frac{2P}{\pi hD}$ (kg/cm^2)	$\geqslant$ 33	$\geqslant$ 1.1
$\frac{\Delta D}{D}$	-	$\geqslant$ 0.033

Some years later, Francken(117)(118) presents results correlating Indirect-Tensile test parameters with road performance. The parameter used was the ratio of Vertical Diametral Strain to Horizontal Tensile Stress, at failure

$$= \frac{\pi L.\ D}{2P}$$

A good linear correlation (r = 0.867) exists between this parameter and rut depth after 5 years heavy traffic.

In France, this test method is used in conjunction with the Duriez,(14)(27) to assess the resistance of mixtures to low temperature cracking. However, the only application to H.R.A. has been in South Africa, in relation to the cracking resistance of overlays(9) and the fatigue resistance of wearing course mixtures,(64) with little published information available.

Inspite of fairly widespread usage, no standard test method has so far evolved, various methods have and are being used and these are summarised in table 9.

2.2.4 The Wheel-Tracking Test Method:

2.2.4.1 Outline of Test Method:

Test specimens, in the form of rectangular slabs are compacted in a steel mould by means of a laboratory roller-compactor which aims to simulate construction rolling.

Testing involves subjecting the compacted specimen, still restrained within the steel mould, to the repeated passage of a wheel, loaded to produce a contact pressure equivalent to that of a heavy commercial vehicle. The depth of the rut which develops with successive passages of the wheel is recorded throughout the test which is conducted at an elevated temperature to simulate the most severe situation likely to be encountered in practise, and also to reduce the time involved in testing.

The essential features of this test which are important in simulating traffic stresses are:

Table 9:

Indirect-Tensile Test - summary of test methods.

Source	Specimen Size	Test Temperature(^{o}C)	Loading Rate (mm/min)	Loading Strips	Measurement
Livneh and Shklarsky(101)	120 x 120 x 60mm Prisms	Room temp.	-	10mm steel	Stress acting on loading strips
Breen and Stephens(102)	Marshall	-20 to 5	6000*	-	Vertical deformation vs. load
Kallas and Riley(39)	Marshall	5 to 60	50.8	13mm steel curved	Indirect-tensile strength
Anderson and Hahn(103)	Marshall	-	1.5	6mm x 5mm plywood	stress - strain
Hudson and Kennedy(97)	101.6 dia x 50mm	0, 25 and 40	50.8	25mm steel curved	Indirect-tensile strength, vert. + horiz. deformation
Maupin(115)	Marshall	Room temp.	25.4	25mm steel	stress - strain
Huet(33)	110mm diameter (minimum)	-10, 25, 45 and 60	18 or 48	No strips (platerns only)	Indirect-tensile strength, vertical deformation.
Marais(65)	Marshall	30 and 40	50	25mm steel curved	Indirect-tensile strength

* refers to a loading rate of 6000 lbs/min.

(i) deformation of the mixture beneath the wheel is partially restrained by the surrounding material

(ii) load is applied by a rolling wheel and, therefore, the contact area is subjected to stresses which vary in both magnitude and direction.

2.2.4.2 Historical Background:

The oldest test of this type was developed at the T.R.R.L., Crowthorne, England. Test specimens 305 x 305 x 50mm are compacted using 32 passes of a steel-clad roller compactor(1) applying a load of 2.68 kg per lineal mm across the width of the specimen. Specimens are then transferred to the Wheel-Tracking Machine itself and tested under the following conditions:

(i) mean contact pressure 520 - 550 kN/m^2

(ii) 42 passes per minute

(iii) distance of travel 250 mm

(iv) test temperature 45°C.

Rut depth is measured periodically at the mid-point of the specimen and Deformation vs. Time curves are produced from which the mean rate of increase in rut depth is determined in mm/hr.
Tests are normally continued for 45 minutes or until the rut depth reaches 15 mm, whichever is shortest.

The above procedure can be modified to permit the testing of 150 mm diameter cores taken from in-service pavements.(54)

Subsequently, several countries have built equipment based on the same principle, but many have simply adopted the apparatus developed by T.R.R.L., notably Spain,(119) Japan(14)(86)(120) and South Africa.(65)

In France(121) and Belgium(118) a somewhat large machine "ornie reur" has been developed to allow 2 parallelepipedic specimens to be tested simultaneous, as does a similar piece of equipment used in Holland.(37)

Similar developments appear not to have been made in the U.S.A., where large scale or miniature test tracks still find preference for simulative testing. However, Csanyi and Fung(42) report the development of a "Traffic Simulator" in which 6 Marshall samples are subjected to the repeated passage of a loaded wheel at elevated temperatures, with the displacement measured after a given number of passages being termed "trafficability".

In addition to the preceeding, many of the large Oil Companies have developed similar facilities. Fabb(91) reports the use by British Petroleum (B.P.) of a Wheel Tracking Machine of the type developed by T.R.R.L. and Verbert(122) refers to a Wheel-Tracking study realised by ESSO Belgium.

Most information in this respect is related to the Asphalt Compaction and Tracking Machine (A.C.T.) developed by SHELL International Petroleum Company Limited and described by Brien.(43) The A.C.T. is based upon the T.R.R.L. original but is designed to compact as well as test specimens. For this purpose the loaded wheel is replaced by a steel-roller segment which can apply a pressure equivalent to an 8 tonne roller. The testing procedure is similar but conditions are somewhat more severe

(i) contact pressure 800 kN/m^2

(ii) 60 passes per minute

(iii) test temperature 60°C.

Testing is continued for 1000 passes and the result reported in terms of the rut depth after 100 passes.

Differences in testing conditions are also found in other procedures(37)(64)(118)(119) due in many instances to a desire to tailor these to suit the area of application. A summary of the different methods and test conditions is given in table 10.

2.2.4.3 Application and Usage:

In the U.K. the Wheel-Tracking test is used to measure the resistance to deformation of dense wearing course mixtures, notably H.R.A. It is considered unsuitable for Macadams and Cold Asphalts whose properties change significantly as a result of traffic and climate.(123)

It is considered by many(11)(56)(57) to be more able to predict a mixture's behaviour under traffic than other test methods and for this reason great emphasis has been placed on its use.
As early as 1958, ranges of Wheel-Tracking rates corresponding to the successful application of B.S. 594 H.R.A. mixtures were presented.(56) Later, on the basis of extensive laboratory-road correlations the following relationship was derived

$$d \leqslant \frac{14000}{N + 100}$$

where d = required Wheel-Tracking rate (mm/hr) at 45°C
N = average number of commercial vehicles per lane per day.

This relationship is defined for roads where the type and range of stress are relatively uniform, such as open stretches of motorway, and corresponds to a level of deformation on the road equivalent to less than 0.5 mm/year.(92) Based on this correlation, tentative limits were proposed by T.R.R.L.,(123) for roads carrying different levels of traffic, see table 11(a). These proposals have subsequently been updated to include higher traffic volumes(124) and these recommendations are presented in table 11(b).

Table 11

Recommended Wheel-Tracking Rates

(a) 1971 - after T.R.R.L.(123)

Commercial Vehicles per day	Maximum Wheel Tracking Rate (45°C) (mm/hr)
under 700	60
700 - 2000	30
over 2000	7

(b) 1979 - after Szatkowski(124)

Commercial Vehicles per lane per day	Maximum Wheel Tracking Rate (45°C) (mm/hr)
750	16
1500	8
3000	4
6000	2
> 6000	< 2

Most work in the U.K. has related to H.R.A., with limited successful extension to asphaltic concrete(54)(125) and Dense Bituminous Macadam basecourse mixtures.(126) On the continent however, application to Asphaltic concrete and Gravel-Bitumen is more common(14) with good correlations between Wheel tracking parameters and rut depths observed under traffic for Asphaltic Concrete in Belgium(118) and Japan.(14)

In addition to establishing promising laboratory-road correlations, extensive back-up work(43)(86)(91) in the laboratory has shown this test method to be capable of detecting changes in mixture performance due to compositional variations. For this reason it is certain to retain its pre-eminent position, in establishing and verifying proposed performance criteria and for the assessment of improved mixtures(127) before they enter Specifications.

Table 10

Wheel Tracking Test - summary of test methods

Location	Specimen Size	Test Temperature (^oC)	Contact Pressure (kN/m^2)	Passes per Minute	Duration	Reporting of Results
T.R.R.L.(123)	305 x 305 x 50mm	45	520 - 550	42	45 mins.	mm/hr
Holland(37)	350 x 120 x 60mm	40	500	-	-	Rut depth and % deformation
France(121)	500 x 180 x 60mm	25, 50 or 60	-	-	100000 passes	rut depth after 100000 passes
Belgium(118)						
Spain(119)	as T.R.R.L.	60	900	as T.R.R.L.	120 mins.	mm/hr and rut depth
Japan(86)	as for T.R.R.L.					mm/hr pass/mm
South Africa(64)	300 x 300 x 50mm	40 and 60	780	50	100 mins.	mm/hr mm^2/min
U.S.A.(42)	Marshall	60	570	25	-	rut depth
SHELL(43)	300 x 300 x 50mm	60	800	60	1000 passes	rut depth after 100 passes
B.P.(91)	as for T.R.R.L.					

2.3 Specimen Manufacture and Testing - Some Important Considerations:

2.3.1 Manufacture of Test Specimens

2.3.1.1 Introduction

The objective when testing bituminous mixtures is to ascertain what physical properties will result in a pavement layer constructed of such a mixture. It is, therefore, essential that the physical characteristics of the compacted test specimen be as nearly as possible identical to those of the mixture in the compacted pavement layer.(128)(129) Failure to achieve this means results obtained may not be valid for the full-scale construction situation.

Over the years many laboratory compaction methods(129)(130) have been developed and may be classified as follows:

Static(32)(130)
Impact(23)
Vibratory(76)
Rolling(1)(44)
Gyratory(131)(132) and Kneading.(133)(134)

The ability of these methods to simulate in-situ characteristics will now be discussed along with other factors which can have an effect upon the results obtained.

2.3.1.2 Density, Particle Orientation and Degradation:

In the past it has been generally considered that a mixture's resistance to applied load is [illegible] a function of density and for this reason methods of compaction were originally developed to produce specimens with densities comparable with those achieved during construction. However, it soon became apparent that the density of in-service pavements increased under traffic(65)(129)(135) and attention was turned to achieving densities equal to those ultimately achieved in service.

The Marshall drop-hammer method of compaction developed by the U.S. Corps of Engineers(50) was typical in this respect. The procedure, requiring the application of 50 blows to each face of the specimen using a 4.535 kg (10 lb) mass hammer falling freely a distance of 457 mm (18 in) onto a 98.5 mm dia (3⅞ in) compaction foot has since been evaluated by several authors.(136)(137)(138)(139) Conclusions regarding its ability to predict the ultimate density attained by in-service Asphaltic Concrete pavements differ considerably. In some applications this method has been found adequate in this respect(51)(136) whilst in others it has been shown not to be capable of achieving the high ultimate densities produced under heavy-aircraft loading(138)(139) and also that it is too severe for the relatively low ultimate densities produced under light vehicular traffic.(137) It, therefore, appears that ultimate density and time under traffic to achieve this is related to traffic loading and intensity, and hence the use of a constant number of blows is not applicable for all applications. For this reason, 3 levels of compaction are specified by the Asphalt Institute,(17) depending on traffic.

For H.R.A., indications are that this material can be more easily compacted to high density than Asphaltic concrete(125) and consequently little change in density from that achieved by good construction rolling will be expected under traffic. This is confirmed by data from Full-Scale Road Trials(65)(66)(93)(140) although they fail to indicate conclusively what level of Marshall compaction simulates the ultimate density in any given situation. However, the limited data available suggests in some instances 50 blows per face(66) is adequate while others indicate 75 blows per face(65) is required.

It should be realised at this stage that density is only one factor to be considered, the effect of particle orientation, aggregate breakage and non-uniform specimen density should also be recognised.(82)

A measure of particle orientation in terms of a "structure index" has been proposed by Puzinauskas(141) but is criticised due to its failure to differentiate between packing structure and particle orientation, and can only, therefore, be considered to give a measure of degree of anisotropy.(142) However, it has been shown, using statistical techniques that in samples of H.R.A. cut from actual construction, aggregate particles are preferentially orientated with their elongation direction almost horizontal,(142) and that such a preferred orientation can be imitated using a laboratory-roller compactor.

During compaction a certain amount of aggregate breakdown occurs (degradation) and this may be quantified in terms of the change in aggregate grading(138) or as a percentage increase in surface-area of the degraded aggregate.(130)

The ability of common methods of compaction to produce specimens with characteristics, akin to those found in a constructed layer, is outlined below:

Static : the high stresses required to achieve small changes in density lead to excessive degradation(130) but very little re-orientation of aggregate particles.(142)

Impact : high stress intensities produce considerable degradation(76) and lead to a fair degree of particle orientation, although there is a tendancy for large particles to align along the sides of the mould.(143)

Rolling : considered by many(129)(142) to produce the same degree of particle orientation and degradation found in actual construction.

Gyratory and Kneading : the shearing action developed within the specimen allows particles to orientate to the same extent as found in practise(130)(132) and at the same time produces the equivalent degradation and high densities attained under very heavy traffic.(138)

For all methods of laboratory compaction there is a tendancy to produce specimens with a non-uniform distribution of density, for 2 reasons:

(i) densification of material adjacent to the mould is hindered and it does not, therefore, attain a density as high as the material at the centre.(141)(144)

(ii) high contact stresses tend to produce higher densities at the top and bottom of specimens.(138)(144)

Density distributions are apparent even in actual construction,(144) although the distributions in moulded specimens differ greatly from this situation it can be simulated using a laboratory-roller compactor.(144)

Regardless of the compaction method used, varying degrees of particle orientation, degradation and non-uniform distribution of density occur. Due to this the specimens produced will have varying degrees of anisotropy, with properties varying depending upon the direction of testing,(29)(101)(141)(144) and this should not be ignored.

2.3.1.3 Size and Shape of Specimens:

In the past, cylindrical specimens have been preferred, an important consideration being that such samples are easier to compact than prismatic specimens.(101) The requirements regarding specimen size can be defined as:

(i) large enough to be representative
(ii) tailored to suit the maximum aggregate size
(iii) proportioned to allow adequate and easy compaction.

Having said this however, size will also effect the values of strength measured by various methods. The effect of height to diameter ratio on measured Compressive Strengths(29) and the results of Uniaxial Creep tests(37) is extensively reported. The sensitivity of Marshall Stability to specimen height is also widely known(50)(145) with correction factors,(2)(17) originally developed by the U.S. Corps of Engineers being applied to specimens of non-standard height. The validity of these original factors has been proven by more recent work(145) which also indicated the necessity to apply corrections to Flow values for specimens of low height, although this was not required for heights close to the standard.

As far as the Indirect-Tensile test is concerned, theoretically, measured strength should be independent of specimen size although results for concrete(100) and other materials(146)(147) indicate that as specimen size increases, the measured strength is reduced and also became less variable. This can be explained by "weak link" theory(100) which states that as size increases the probability of a specimen containing points or planes of weakness increases and, therefore, large specimens will in all probability fail at a lower stress. In general the observed decrease in strength with increasing volume follows Wiebul Theory.(107)(148)

The size and shape of specimens used in the past has generated major criticisms in that the specimen size, particularly the thickness, is much greater than that of actual pavement layers, and that this leads to problems associated with relating results from such specimens to the practical situation. To overcome this, attention has recently turned to the fabrication of rectangular slabs with thicknesses equivalent to that of pavement layers. In this respect Swanson et al(149) suggest a slab with an area of 300 x 300 mm to be the smallest area which still simulates a continuous pavement layer.

2.3.1.4 Type and Amount of Compaction:

It is desirable that test specimens yield strength values equivalent to those of pavement cores, i.e. the in-situ strength. Results indicate that Marshall Stability values for specimens compacted by the drop-hammer method differ greatly from those obtained for pavement cores of equivalent density.(138) However, Stabilities equivalent to those of pavement cores are obtained for specimens compacted to the same density using a Kneading compactor(138) or cored from slabs produced by a laboratory roller compactor.(149) The high stability values of impact (Marshall) specimens' results from the structure developed in the specimen during moulding, with the same being true for Statically moulded specimens.(144)

Leaving aside field behaviour, it is apparent that different methods of compaction greatly influence the results obtained using many test methods.(35)(80)(128)(150)(151) It has been concluded that the influence of compaction can be greater than that of aggregate grading, binder content, etc.(128) and that for Empirical tests in particular, closer agreement between tests is found if a single method of compaction is used.(128) It should also be noted that for the Marshall drop hammer method, it is reported that 40 blows of an automatic compactor is equivalent to 50 blows using the manual procedure.(152) Further, small variations in the equipment used, in particular the compaction pedestal can influence results to a large extent.(153)

The resulting density produced in a specimen will depend upon the compactive effort (amount of compaction) applied and this is usually controlled such that a density equivalent to that achieved in practise is obtained.

In general as compactive effort is increased, be it number of blows, number of passes, or force applied the density achieved will increase, rapidly at first then tend to level off. This has been shown to be the case for Marshall compaction(152)(154)(155) and Laboratory roller compaction(125)(154) and in both cases this increase in density has been accompanied by an increase in Stability(152)(154)(155) and resistance to deformation,(125)(154) respectively. It is important to note that a fall of 1% in degree of compaction produces a reduction in stability of 15 - 20%.(79) The relationship between number of blows and density under Marshall drop-hammer compaction has been used by several authors(156)(157)(158) to quantify the ease with which a mixture can be compacted.

Considering now the effect on mixture properties over a range of binder contents when compactive effort is altered. For both Asphaltic Concrete and H.R.A. the following changes (more marked for Asphaltic Concrete) occur as compactive effort is increased:(125)

(i) values of maximum density and maximum stability increase
(ii) binder contents to produce maxima decrease
(iii) optimum binder content decrease
(iv) Flow is relatively unaffected.

Similar reductions in optimum binder content with increasing compactive effort is reported for mixtures compacted by laboratory roller compaction.(159)

2.3.1.5 Mixing and Compaction Temperatures:

Temperature has a marked effect upon the viscosity of bituminous binders(1)(160) and control of temperatures is, therefore, of great importance. During mixing sufficient "fluidity" is required to ensure adequate coating of aggregate. The effectiveness of coating,(161)(162) binder film thickness,(163) etc. will have an effect upon the physical properties of the specimen produced. Available literature(164)(165) indicates for mixtures compacted by the Marshall method, as mixing temperature increases, density increases to a peak and then falls while Stability over the same range continues to increase, at higher temperatures the increase in Stability is attributed to hardening of the binder.(164)

During compaction, the binder acts as a lubricant to aid densification of the aggregate structure and various authors(46)(79)(164)(165)(166) have reported the effect of compaction temperature on the resulting physical properties. In general, as compaction temperature increases so does density, with indications that at some point it begins to decrease.(164) Accompanying this is a rise in measured strength(149)(164)(166) again with a tendancy to decrease at some point.(164)(166) The effect of compaction temperature on strength is related closely to method of compaction used, the effect being greatest for impact methods decreasing by half for kneading compaction and being negligible for roller compaction.(149)

As far as Mix Design is concerned, high compaction temperatures result in the determination of lower Marshall optimum binder contents,(1)(167) presumably the higher densities achieved at high compaction temperatures effect results in the same way as increased compactive effort.

The preceeding highlights a need for strict control over mixing and compaction temperatures. A method favoured for this is the specification of equi-viscous mixing and compaction temperatures, as is done by the Asphalt Institute(17) but as yet, however, B.S. 594 contains only a range of temperatures for these operations dependent solely upon the grade of binder used. Certain suggestions regarding this however have been made(125)(168) and these are included along with current specified values from elsewhere, in table 12.

Table 12

Requirements for Mixing and Compaction Temperatures

Source	Mixing temperature to produce a viscosity	Compaction temperature to produce a viscosity
Asphalt Institute(17)	85 ± 10 secs Saybolt - Furol	140 ± 15 secs Saybolt - Furol
Netherlands(79)	170 mm^2/s (cSt)	280 mm^2/s (cSt)
Jacobs(125)	2 poises	4 - 5 poises
Brien(168)	4 poises	10°C below mixing temperature

2.3.2 Method of Testing Specimens:

2.3.2.1 Introduction

A general summary of available test methods has already been given, in the following sections some important points regarding the execution of these procedures are raised.

2.3.2.2 Mode of Load Application

For Empirical methods this is of little importance as by definition any conclusions drawn from the results should be based upon extensive laboratory - field correlations.

However, for Fundamental methods this is of great importance as a precise knowledge of the stresses acting during the test is required. The Indirect-Tensile test is worthy of consideration in this respect as the situation is somewhat complex. The deviations from the assumed conditions and their effect have already been discussed, but questions still arise as to the effect of the composition and width of the loading strips upon the stress distribution, measured strength and mode of failure. These effects have been investigated in detail for various materials and it is generally considered that distributing the load has little effect on the stress distribution at the centre of the specimen.(169)(170)(171) For brittle materials (concrete, etc.) results regarding the composition of the loading strips are inconclusive, in some cases soft materials are reported to produce higher strengths and more dispersion(171) while in others the opposite is found.(99) Regarding the width of the loading strip it was found that as this is increased, failure is induced closer to the centre of the specimen(169)(172) prompting the conclusion that the test gives a valid measure of tensile strength provided failure is initiated at or close to the centre of the specimen.(170) Work with Asphaltic Concrete(97)(104) indicated that the composition and width of the loading strips had little effect on measured strength values although increasing the width did reduce scatter.

As for simulative methods, the mode of loading should be such as to simulate in-service conditions. The dimensions of the wheel and the applied load will have an effect upon the contact area and contact stress in the Wheel-Tracking test and should, therefore, be controlled to suit requirements.

2.3.2.3 Loading Rate and Test Temperature

The mechanical properties of bituminous mixtures are greatly affected by temperature and rate of loading as a direct result of the visco-elastic nature of the bituminous binder.

Numerous authors have reported the effect of these on the results of several tests including the Unconfined compression test,(176)(177) the Marshall test,(152)(167)(178) the Indirect-tensile test(97)(104) and Wheel-Tracking test.(92)(120) In general, as test temperature increases the values of measured strength decrease and in particular a 15°C increase in temperature produces a ten-fold increase in the observed rate of deformation in the Wheel-Tracking test.(92)

Increasing the rate at which load is applied has the effect of increasing the values of measured strength(97)(179) although this effect is not as great as the effect of temperature and is reduced by providing the specimen with some degree of lateral support.(179) In the Wheel-Tracking test the time of loading and time between applications is a function of the speed of the wheel. For H.R.A.'s as the time of loading increases, the measured resistance to deformation decreases(120) which implies that mixtures tracked at high speeds will appear more resistant to deformation than those tracking at low speeds.

In the past it has been common practise to carry out mechanical test on Bituminous mixtures using apparatus which applies load at a constant rate of strain, whilst the specimen is maintained at a constant temperature.

In the U.S.A. 60°C (140°F) has normally been adopted as it is considered to represent the most severe in-service condition likely to be encountered. In the U.K., indications are that 45°C is more representative of this condition(180)(181) and this has, therefore, been adopted for Wheel-Tracking tests,(123) although B.S. 594(7) continues to specify 60°C for the Marshall test.

A somewhat different situation arises concerning the Indirect-Tensile test which is normally applied to brittle, elastic materials. It is clear that at high temperatures and low rates of loading the behaviour of Bituminous materials will deviate considerably from this.(173) Results indicate however that over a wide range of temperatures and loading rates samples of Asphaltic Concrete failed due to tensile stresses(97) in an acceptable manner and there is, therefore, no reason why it should not be applied to such materials.

CHAPTER 3

OUTLINE OF EXPERIMENTAL PROGRAMME

3. OUTLINE OF EXPERIMENTAL PROGRAMME

3.1 Introduction

In Chapter 1 attention was drawn to problems related to the resistance to deformation of H.R.A. surfacings and to certain inadequacies of the "recipe" method of specification for such mixtures, in particular an inability to cater for the differing binder requirements of different fine aggregate sands. Moreover, with the introduction of the Marshall Test into B.S. 594 (1973), to permit the determination of an "optimum binder content" for the actual materials (sand, filler, binder) to be used, it was hoped that the resulting mixtures would have improved Engineering properties and in particular an increased resistance to deformation under heavy traffic.

The Marshall Test is, of course, only one of many mechanical test procedures, which could be applied to this same end.
The motivation for and overall aim of the present investigation was, therefore, to determine the ability of three mechanical test procedures to:

(a) assist in the selection of suitable mixture proportions, and in particular the binder content required to obtain the best compromise between durability and maximum resistance to deformation, for a given set of constituent materials

(b) predict/determine the properties of mixtures having good resistance to deformation, but in particular to establish a relationship between Marshall parameters and resistance to deformation, for a range of H.R.A. wearing course mixtures.

3.2 Mechanical Test Procedures Employed

Three mechanical test procedures, namely, the Marshall test, Indirect Tensile test and Wheel-Tracking test are considered in this investigation, each for the following reasons:

(a) Marshall test: this inclusion was of greatest importance in view of its recent inclusion in B.S. 594 and also because there is little reported information regarding its application to H.R.A. mixtures.

(b) Indirect-tensile test: investigation of this test method was suggested by the Collaborating Establishment, ESSO Petroleum Company Limited, in the light of promising work on the continent of Europe.(33)

(c) Wheel-tracking test: this test method was included due to the desire to consider a test method which simulated the practical loading condition, the results of which could be used as a "yardstick" to judge a mixture's ability to resist deformation under traffic.

3.3 H.R.A. Mixtures Considered

A series of H.R.A. wearing course mixtures covering the range of Stone Contents permitted by B.S. 594(7) were investigated. For each Stone Content, mixtures were tested over a narrow range of binder content, not, however, too narrow as to preclude the determination of an "optimum binder content" for the particular Stone Content under consideration. The Stone Contents and range of binder contents considered, are summarised in table 13.

TABLE 13

RANGE OF MIXTURE COMPOSITIONS CONSIDERED IN MAIN INVESTIGATION[+]

	Test Method \ Stone Content	0	10	20	30	40[*]	55
SAND A	Marshall	9.5-15.0[x]	8.5-12.5	7.0-11.0	5.5-11.5	5.5-9.5	3.5-7.5
	Indirect-Tensile	9.5-13.0	8.5-12.5	7.0-11.0	6.0-10.0	5.5-9.5	3.5-7.5
	Wheel-Tracking	N/T	N/T	N/T	6.0-11.0	5.5-9.5	3.5-8.0
SAND B	Marshall	5.5-9.5	4.5-8.5	4.0-8.0	4.0-7.5	3.0-7.0	3.0-6.5
	Indirect-Tensile	5.5-10.0	4.5-8.5	4.0-8.0	4.0-7.5	3.0-7.0	3.0-5.5
	Wheel-Tracking	N/T	N/T	N/T	4.0-7.5	4.0-7.0	3.0-6.5

[*] Stone content %age by mass of total mixture. For mixtures containing Sand B; 38% is used in place of 40%.

[x] Range of binder content considered, % by mass of total mixture.

[+] Only mixtures comprising the main investigation are tabulated here, additional mixtures considered will be referred to in the text.

N/T Not tested.

Marshall and Indirect-tensile tests were carried out over the whole range of Stone Contents, while Wheel-Tracking tests were limited to mixtures containing 30% stone and above. This was primarily done in order to reduce the time involved in manufacture and testing of specimens, but also because it was considered that in practise only such mixtures would be considered for use under heavy traffic.

In the manner outlined above it was hoped to determine how the mixture properties resulting from a given combination of constituent materials varied as binder content was altered over a fairly narrow range which included the binder contents likely to be used in practise. From such results it should also be possible to establish correlations between different mixture properties, for the same limited range of binder content. This approach is considered by the author to improve upon those used in similar investigations reported elsewhere, in which results, for what may be considered "individual" mixtures, of varying type and composition have been brought together. This has resulted in a very wide range of mixture properties being considered with mixtures varying from very resistant to very susceptible to deformation, being used to establish correlations between the various tests considered. Giving consideration to the scatter of results in what maybe termed the practical range, this tends to indicate that previous work is saying, the test methods considered are capable of telling "chalk from cheese" but little else. Results of this nature are useful, in that they identify the presence of such correlations, but until similar relationships can be identified for the ranges of binder content of the order of those used in this work, little practical value can be obtained due to the high scatter of results.

3.4 Comparison of Laboratory and Road Results

If any degree of confidence is to be placed upon laboratory test results, it is essential that such results are correlated with actual road performance, in order to answer such questions as:

(a) Is the "optimum binder content" determined in the laboratory equal to the binder content giving "optimum" performance under road conditions?

(b) What limits should be set on the values of test parameters measured in order to ensure the production of mixtures with the desired degree of resistance to deformation under given traffic and climatic conditions?

In an attempt to establish some correlation between laboratory and road results, the constituent materials for the mixtures investigated were the same as some of those used by the T.R.R.L. in a full-scale road trial on the A33 Winchester by-pass.(59) Throughout the Sheffield investigation, mixtures were manufactured using the same coarse aggregate, filler and binder as used at Winchester and two of the fine aggregate sands. The sands used in this investigation were chosen following discussions at T.R.R.L. in early 1978, when it appeared that mixtures made with these materials and laid at Winchester, were showing signs of providing meaningful data more quickly than sections containing other sands. It should be pointed out that in order to confirm any relationships indicated, it was originally intended to utilise three sands from the A33 experiment, but in the event lack of time prevented this.

The H.R.A. mixtures laid at Winchester contained 30% stone, so to facilitate the correlation, laboratory tests on 30% stone mixtures were conducted over a range of binder contents which included those found on analysis in the sections on the A33.

3.5 Statement of Aims and Objectives

The overall aims of the investigation have been referred to previously. To recap, they are:

(a) To assess the ability of the three test methods considered, to assist in the selection of an "optimum" mixture composition, regarding durability and, in particular, resistance to deformation.

(b) To determine the properties of H.R.A. mixtures having good resistance to deformation, but, in particular, to establish a relationship between Marshall parameters and resistance to deformation.

In order to achieve these overall aims the attainment of a number of secondary objectives was anticipated during the course of the investigation, namely:

(a) The development of suitable specimen manufacture and testing procedures.

(b) A critical appraisal of specimen manufacture and testing procedures, along with the associated analysis of test results employed.

(c) Formulation of methods of selecting "optimum binder contents," from test results.

(d) Assessment of the validity of extending the Marshall mix design (as per B.S. 594) to stone-filled mixtures.

(e) Correlation of Marshall test and Indirect Tensile test results over the range of stone contents considered.

(f) Correlation of Marshall test and Wheel Tracking test results for the high-stone content mixtures.

CHAPTER 4

MATERIALS AND SPECIMEN COMPOSITION

4. MATERIALS AND SPECIMEN COMPOSITION

4.1 Introduction

The samples of H.R.A. used in this investigation were manufactured from constituent materials; coarse aggregate, fine aggregate, filler and binder, nominally the same as those comprising mixtures laid in the A33 Winchester by-pass experiment 1972. Reference to the T.R.R.L. laying report (59) for the A33 experiment enabled the material suppliers to be identified. They were then contacted and arrangements made to collect sufficient quantities of each material, to enable the completion of the investigation.

Prior to commencement of the main experimental work, the materials were first subjected to a number of routine tests in order to ascertain if their properties were significantly different from those of the materials used in 1972. The results of these analyses are given in the following sections. Also included are results of similar tests conducted at the ESSO Research Centre, Abingdon, (E.R.C.A.), on different samples of the same materials, obtained for co-operative work carried out at E.R.C.A. during the summer of 1978.

Samples of coarse aggregate, fine aggregate and filler were taken and reduced to the required size for testing in accordance with B.S. 812 part 1,(182) and the tests conducted in accordance with B.S. 812 parts 1(182) and 2(183).

4.2 Coarse Aggregate

This is defined by B.S. 594 (1973) as "material substantially retained on a 2.36mm B.S. test sieve."

The coarse aggregate used was a 14mm nominal size, Basalt, crushed rock aggregate, supplied by:

John Wainwright & Company Limited,
Moon's Hill Basalt Quarries,
Stoke St. Michael,
Nr. Shepton Mallet,
Somerset.

4.2.1 Sieve analysis - particle size distribution.(182)

Results are given in table 14, with the grading limits given in B.S. 594 included for comparison. The latter relate to wearing course mixtures containing 30% by mass of 14 or 20mm nominal size coarse aggregate, laid to a nominal thickness of 40mm. The mixtures in the A33 experiment, were laid to a "target" thickness of 38mm.(59)

TABLE 14

Coarse aggregate grading.
(number of determinations shown in brackets).

B.S. Sieve Size (mm)	Percentage passing by mass		
	Sheffield (6)	E.R.C.A. (3)	B.S. 594 Table 2
28	100	100	100
20	100	100	85 - 100
14	90	88	0 - 100
10	11	10	0 - 60
6.3	0	0	-

The material complies with B.S. 594 grading requirements, and the suppliers indicate(184) that the grading has not changed significantly since 1972. It is, therefore, anticipated that the grading is not significantly different from that of the material used in the A33 experiment.

4.2.2 Relative Density and Water Absorption.(183)

The mean values of three tests on duplicate samples are given below. The figure in brackets is that quoted by T.R.R.L.(59)

Relative density on an oven-dry basis	=	2.71
Relative density on a saturated surface-dry basis	=	2.72
Apparent relative density	=	2.76 (2.77)
Water absorption (% dry mass)	=	0.7

4.3 Fine Aggregate

This is defined as that portion of the mineral aggregate which passes a 2.36mm B.S. test sieve and is retained on a 75µm B.S. test sieve. Two types of fine aggregate were used in this investigation, both of which were siliceous sands.

Sand A: was comprised of grains of quartzite, quartzitic sandstone and quartz, and appeared light pinkish-brown in colour, supplied by:

E.C.C. Quarries Limited,
Rockbeare Pit,
Nr. Ottery St. Mary,
Devon.

Sand B: was comprised of uncrushed sub-rounded chert with quartz and flint, it appeared medium-brown variagated in colour, supplied by:

Hall Aggregates (Thames Valley) Limited,
Staines Lane,
Chertsey,
Surrey.

4.3.1 Sieve analysis - Particle-size distribution(182)

Results for "as received" samples of sands A and B are given in tables 15 and 16 respectively, the grading limits given in B.S. 594 (1973) are included for comparison.

It can be seen that sand A complies with the requirements of B.S. 594, and maybe considered a typical "asphalt" sand. However, sand B fails to meet these same requirements, due in particular to a high percentage (17%) retained on a 2.36mm sieve. The gradings of both sands differ only slightly from those quoted by T.R.R.L.,(59) and it is considered justifiable to consider these materials as being nominally the same as those used in the A33 experiment.

Further, if the portion of sand B, retained on a 2.36mm sieve is removed, the material takes on the grading indicated in table 17. This is somewhat closer to the B.S. 594 requirements, but nevertheless, still fails to comply with them. These "as received" and "modified" gradings will be referred to later. Grading curves, plotted from the information contained in the tables previously referred to, are presented in figure 3.

TABLE 15

Grading of Sand A

(Number of determinations shown in brackets)

B.S. sieve Size	Percentage Passing by Mass			
	Sheffield (8)	E.R.C.A. (2)	T.R.R.L.	B.S. 594 Table 3
5mm	100	100	100	100
2.36	100	100	100	95 - 100
1.18	99	99	99	
600 microns	95	95	97	75 - 100
425	89	-	92	
300	61	64	70	
212	33	35	33	15 - 60
150	15	14	18	
75	2.5	3.5	2.9	0 - 5

TABLE 16

Grading of Sand B "as received"

(number of determinations shown in brackets)

B.S. sieve Size	Percentage Passing by Mass		
	Sheffield (8)	T.R.R.L.	B.S. 594 Table 3
5mm	100	100	100
2.36	83	85	95 - 100
1.18	68	74	
600 microns	54	59	75 - 100
425	42	44	
300	19	25	
212	8	8	15 - 60
150	3	4	
75	0.7	0.6	0 - 5

Grading of Fine Aggregates used in Investigation

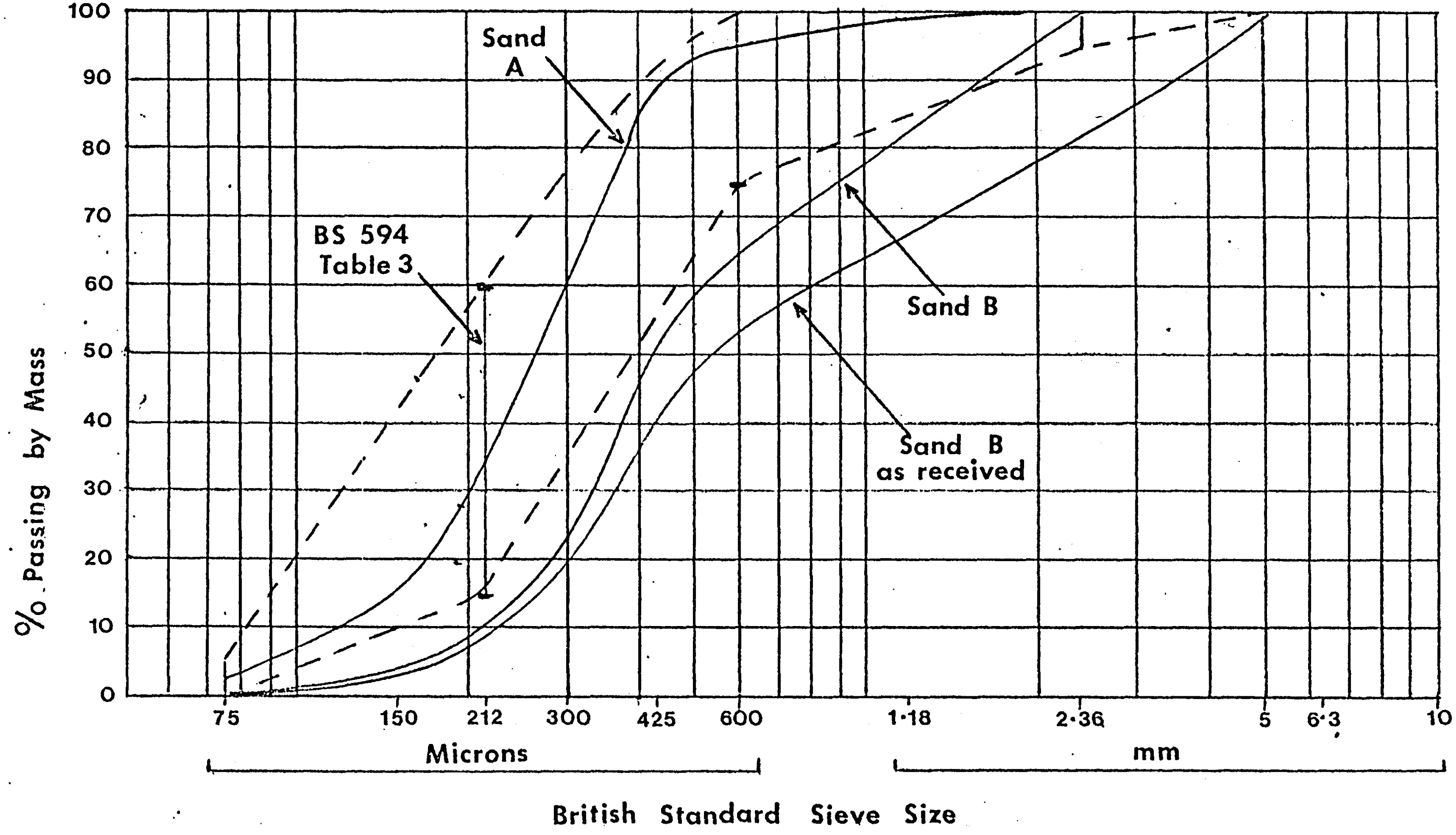


Fig.

TABLE 17

Grading of Sand B - plus 2.36mm portion removed

B.S. Sieve Size	% Passing by Mass
5mm	100
2.36	100
1.18	82
600 microns	65
425	51
300	23
212	10
150	4
75	0.8

4.3.2 Relative Density and Water Absorption(183)

The mean values of two tests on duplicate samples, for each sand, are given below, the figures in brackets are those quoted by T.R.R.L.(59)

For Sand A:

Relative density on an oven-dry basis = 2.57

Relative density on a saturated surface-dry basis = 2.61

Apparent relative density = 2.66 (2.66)

Water Absorption (% dry mass) = 1.4

For Sand B:

Relative density on an oven-dry basis = 2.56

Relative density on a saturated surface-dry basis = 2.59

Apparent relative density = 2.67 (2.67)

Water Absorption (% dry mass) = 1.3

4.4 Filler

This is defined as the portion of the mineral aggregate which passes a 75μm B.S. test sieve.

The filler used was a crushed limestone, supplied by:

Francis Flower and Son Limited,
Gurney Slade Quarries,
Gurney Slade,
Nr. Bath,
Somerset.

4.4.1 Percentage Passing a 75μm sieve(182)

The current B.S. 594 requires 85% by mass of the added filler to pass a 75μm B.S. test sieve. The results in table 18 indicate that the material used meets this requirement and that the value found on analysis agrees with that quoted by T.R.R.L.(59)

TABLE 18

Filler: %age passing 75μm sieve

	Sheffield (4)	E.R.C.A. (2)	T.R.R.L.
% passing 75μm sieve by mass	88	88	88

Figures in brackets indicate the number of determinations conducted.

4.4.2 Relative Density(183)

The mean value of 2.70, found on analysis, for two duplicate determinations, is in agreement with the value quoted by T.R.R.L.(59)

4.5 Binder

The binder used in the A33 experiment was a 50 penetration grade Petroleum bitumen from a Middle East crude source, supplied by the SHELL International Petroleum Company Limited.(185) A sample of this material was obtained from T.R.R.L. by E.R.C.A. and a binder "matched" to it was produced and supplied by:

ESSO Petroleum Company Limited,
Fawley Refinery,
Southampton.

The "matched" binder was sampled and tested according to the relevant British Standard or Institute of Petroleum Standard, test results are given in table 19:

TABLE 19

Binder Properties

(Figures in brackets indicate reference of the relevant test standard.)

	Property	Sheffield	E.R.C.A.	T.R.R.L.
(186)	Penetration (25° C)	57	58	-
(187)	Softening Point (° C)	51	51	56
(173)	P.I. (nomograph)	0.3	0.3	0
(188)	Permittivity (25° C)	-	2.663	2.685

Each value is the mean for duplicate determinations.

The relative density was also determined according to I.P. 190,(189) the mean of three duplicate determinations gave a value of 1.03.

All things considered, the properties of the "matched" binder, do not differ greatly from those of that used in the A33 experiment.

4.6 Specimen Composition

4.6.1 General

The ranges of Stone content and binder content to be considered have been described in the previous chapter.

Throughout the investigation the composition of test specimens was as follows:

(a) For "mortar" mixtures containing 0% stone, each specimen comprised a given percentage by mass of the total mix, binder (wb), fine aggregate, passing a 2.36mm sieve and sufficient added filler to bring the proportion of aggregate retained and aggregate passing a 75μm sieve to 6:1. This ratio was maintained constant as binder content was varied, as specified in Section 3 of B.S. 594 (1973).(7)

(b) For "Stone-filled" mixtures containing a given percentage by mass of the total mix, coarse aggregate (w_1), the sand/filler ratio was maintained constant at 6:1, whilst both w_1 and w_b were varied. Consequently, each specimen was comprised w_1 % stone and w_b % binder, (percentages by mass of the total mix), and sufficient quantities of fine aggregate and filler to produce a 6:1 ratio of material passing a 2.36mm sieve and retained on a 75μm sieve, to material passing a 75μm sieve. Such a composition is shown diagrammatically in figure 4 (a).

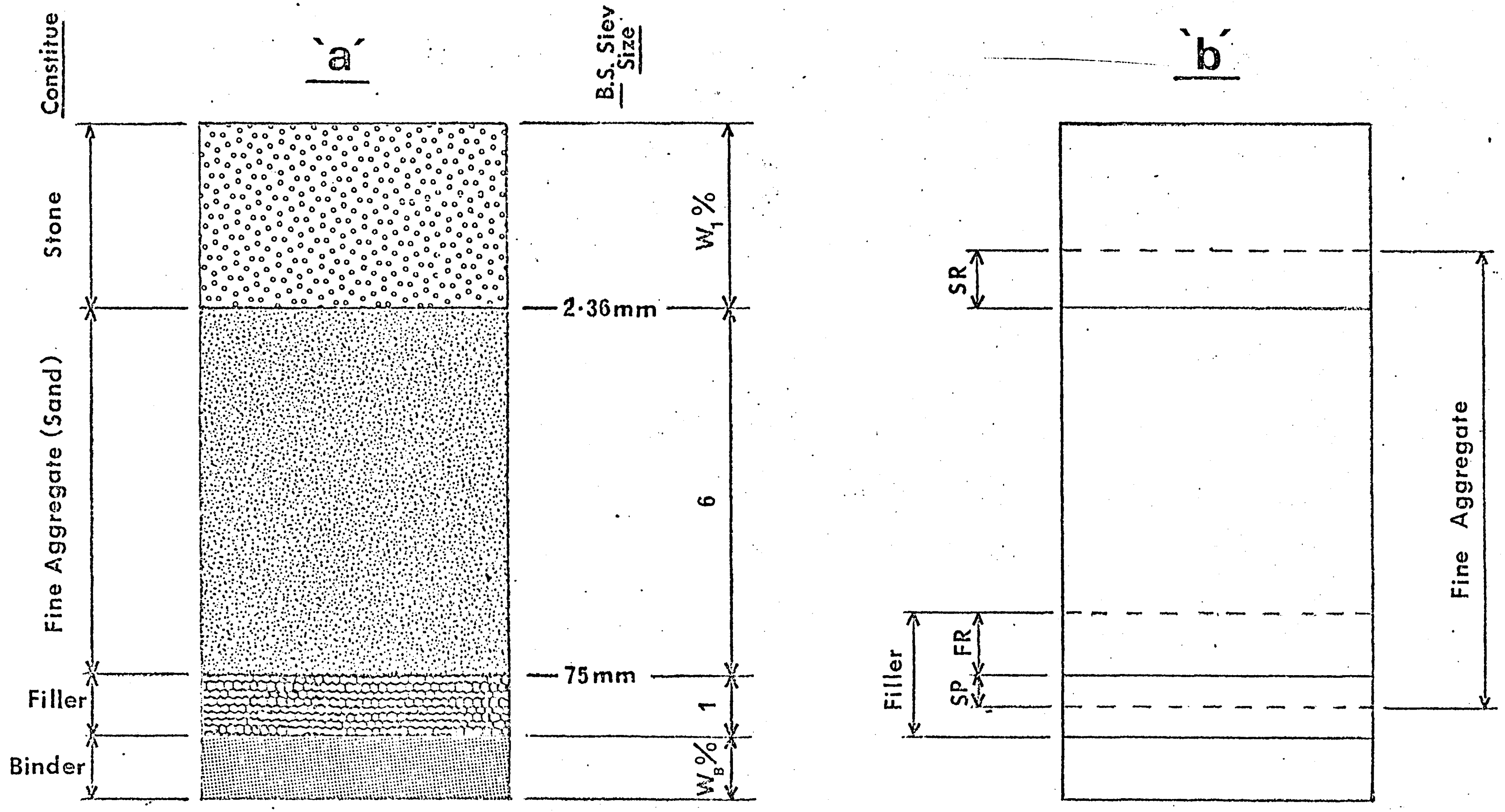
4.6.2 Calculation of Specimen Proportions required

As w_1 and w_b are expressed in terms of % by mass of total mix, a knowledge of the total mass of the mix (Wm) is required in order to calculate the mass of each constituent to be combined to produce the desired overall specimen composition.

As Marshall test specimens are required to have a height of 63.5 ± 1.5mm,(7) it was necessary to determine, by means of trial mixes, the value of Wm required to produce specimens within this range, for each w_1 and w_b used. A series of specimens were made up, having differing Wm's and with binder contents at the centre and extremes of the range selected. The height of each compacted specimen (H) was determined and compared with that specified. From such data the values of Wm required at each binder content were estimated. This procedure is illustrated in table 20, for mixtures containing sand A, crushed limestone filler and $w_1 = 0$, over a range of w_b.

With Wm obtained in the above manner it follows, for a "mortar" mixture, that,

$$Wm = Ws + Wf + Wb \qquad (1)$$



Mixture Composition

Where Ws = mass of sand

Wf = mass of filler

Wb = mass of binder.

$$\text{Mass of binder required (Wb)} = \text{Wm} \times \left(\frac{\text{Wb}}{100}\right) \text{ grams} \qquad (2)$$

hence

$$\text{Mass of fine aggregate plus filler (Wsf)} = \text{Wm} - \text{Wb} \text{ grams} \qquad (3)$$

Wsf must be proportioned such that 85.71%, (6/7) is retained on a 75µm sieve. This calculation is complicated by the fact that in the case of both sands used, part of the fine aggregate passes a 75µm sieve (SP), and this portion must, therefore, be considered part of the filler. Further, part of the filler is retained on a 75µm sieve (FR) and, therefore, must be considered as part of the fine aggregate. This situation is illustrated diagrammatically in figure 4 (b).

To calculate the proportion of sand required in Wsf (Y), a knowledge of the following is required:

(a) %age of filler retained on a 75µm sieve = (FR)
(b) %age of sand retained on a 75µm sieve = (CR)
This data is available from sieve analysis results.

$$\text{then} \quad Y = \frac{85.71 - \text{FR}}{\text{CR} - \text{FR}} \qquad (4)$$

TABLE 20

Trial Mixes - to determine required specimen mass.
0% Stone - Sand A.

(a) Binder content 12.0%

Wm (grams)	H (mm)	Remarks
1000	60.2	Too small
1100	63.8	Use 1100g as height is close to mid-range value
1200	67.1	Too large

(b) Binder content 9.5%

1000	63.6	Both heights fall within specified range. Use 1000g as it is closest to mid range
1050	64.8	
1100	66.7	Too large

(c) Binder content 15.0%

1100	60.1	Too small
1150	61.6	Too small
1200	63.4	Use 1200g as it is close to mid-range value

(d) Total specimen masses - estimated from the above results.

Wb (%)	Wm (grams)
9.5	1000 *
10.0	1020
10.5	1040
11.0	1060
11.5	1080
12.0	1100 *

Wb (%)	Wm (grams)
12.5	1100
13.0	1120
13.5	1140
14.0	1160
14.5	1180
15.0	1200

* Values determined above.

hence

mass of sand required (Ws) = Wsf x Y grams. (5)

and proportion of filler required in Wsf (Z)

= 1 - Y (6)

hence

mass of filler required (Wf) = Wsf x Z grams (7)

Following these calculations through for a specimen containing 9.5% by mass binder, crushed limestone filler, 0% stone and sand A we find:

from table 20, Wm = 1000 grams.

hence $Wb = 1000 \times (\frac{9.5}{100}) = 95.0$ grams

and $Wsf = 1000 - 95 = 905$ grams

from table 18, FR = 12.0% and from table 15, CR = 97.5%

hence $Y = \frac{85.71 - 12.0}{97.5 - 12.0} = 0.8621$

hence $Ws = 905 \times 0.8621 = 780.2$ grams

and $Z = 1 - 0.8621 = 0.1879$

hence $Wf = 905 \times 0.1879 = 124.8$ grams

When considering "mortar" mixtures, it was required that all of the aggregate passed a 2.36mm sieve, this requirement was met for sand A but entailed the screening of sand B in order to remove the plus 2.36mm material. Any calculations were, therefore, based upon the grading given in table 17, and not the "as received" grading shown in table 16.

Extending the preceding to "stone-filled" mixtures, containing w_1 % coarse aggregate, equation (1) becomes:

$$Wm = Wst + Ws + Wf + Wb \qquad (8)$$

where Wst = mass of coarse aggregate.

hence

$$Wst = Wm \times (\frac{w_1}{100}) \text{ grams} \qquad (9)$$

and hence equation (3) becomes:

$$Wsf = Wm - (Wst + Wb) \text{ grams.} \qquad (10)$$

For mixtures containing sand A, calculation continues as before, to determine Ws and Wf. However, the situation regarding sand B is complicated by the fact that there is a significant fraction of plus 2.36mm material (SR), which must be considered as part of the coarse aggregate, see figure 4 (b). This being the case, having determined Ws, in the manner indicated previously, using the "modified" grading, table 17, it is necessary to determine the mass of plus 2.36mm material (Wsr) that would be present, had it not been removed.

$$Wsr = Ws \left[\frac{1}{(\frac{100 - SR}{100})} - 1 \right] \text{ grams}$$

and hence the mass of actual coarse aggregate to be added (Wst^1), to bring the stone content up to w_1% is equal to:

$Wst^{1} = Wst - Wsr$ grams.

In some cases, where the stone content was low, Wsr was found to be greater than the required value of Wsb, and in such instances the addition of actual coarse aggregate was not necessary and Wst was comprised totally of that portion of the sand retained on a 2.36 mm sieve.

Hence, when preparing stone-filled mixtures containing sand B, the fraction retained on a 2.36mm sieve was first removed and the required amount (Wsr) recombined at a later time.

A computer programme (Mix 1) was developed at this stage primarily to speed up the calculation of specimen proportions but also to remove any errors which may occur in the course of manual calculations and to be stored for future use. Full details of this are given in Appendix A, along with sample out-put.

4.6.3 Specimen Identification

From the point where the mixture proportions were determined, each specimen (mixture composition) was given an identification number so that all data related to that particular mixture could be kept track of.

The identification system adopted is outlined below:

e.g. 30A 15.0M.1

This refers to a 30% stone content mixture (30), using sand A (A), having a binder content of 15.0% (15.0) and tested using the Marshall method (M). The final figure (1) indicates this is the first of a pair of duplicate specimens. Thus describing fully the mixture and test method, a similar mixture tested by the Indirect-Tensile test method would be identified by a (T) in place of (M), and similarly a wheel-tracking specimen by a (W).

5. EXPERIMENTAL PROCEDURES:

5.1 Introduction:

The methods used in this investigation for the manufacture and testing of specimens are described in the following sections, with particular attention being given to the development of the techniques and apparatus used. To compliment this, a more detailed, step-by-step method for each test is included in Appendix B. Considerable attention is paid to the development of the Marshall Test procedure as much of the equipment, and many of the techniques and lessons learned are applicable to the other two test methods.

5.2 Storage of Constituent Materials:

Prior to the start of any experimental work consideration was given to the manner in which the constituent materials were to be stored.

In order to prevent any dust produced during the handling and testing of the aggregates and filler from contaminating samples and equipment being used in the main laboratory, these constituents were stored in a room separate from the main laboratory. This room was equipped with the apparatus necessary to conduct routine tests and to facilitate batching of the aggregates and filler prior to mixing.

Coarse aggregate and fine aggregate were stored in labelled sacks until required when sufficient quantities were oven dried and placed in separate labelled storage bins. The filler was oven dried and stored in airtight containers.

The binder to be used was supplied in 12.5 kg. kegs, these were labelled and stored in a small room also separate from the main laboratory. This location was chosen as it remained relatively cool and was out of direct sunlight.

Throughout the course of the investigation, periodic tests were made on samples of all materials to check that their properties, particularly the aggregate grading and binder penetration did not change significantly.

5.3 The Marshall Test:

5.3.1 Introduction

The author was fortunate in that the basic equipment required to carry out the Marshall Test was available at the onset.
It was decided that the Marshall Test would be conducted in accordance with Section 3, B.S. 594 (1973),(7) with modifications to the procedure given in B.S. 594 being made where it was considered appropriate. An investigation based upon "trial and error" was undertaken whereby:

1. varying the techniques used
2. modifications to apparatus used
3. experience gained

would lead to the development of a suitable sequence of operations for the manufacture and testing of specimens.

5.3.2 Preparation of Constituent Materials

Any coarse aggregate to be used was thoroughly shaken on a 2.36mm sieve to remove any dust present and the fine aggregate was screened to remove any plus 2.36mm material. In the case of Sand B the plus 2.36mm material was retained and stored separately.

The aggregates and filler were then sampled and prepared according to B.S. 594 (3.4.2.3.), the required quantities (4.6.2.) of each, sufficient for a single specimen, were weighed out to the nearest 1 gram and placed in a suitable container which was then labelled with the appropriate specimen identification number (4.6.3.). The binder was heated and decanted into small containers, one per specimen, covered and allowed to cool.

The type of container used for the binder was found to be important. Small paint tins presented problems due to the presence of a "lip" around the inside of the tin which made it difficult to control the quantity of binder being poured from the tin. It was also difficult to remove the lids of such tins when working in heat resistant gloves. Suitable tins (90mm diameter x 90mm) with slip on lids were eventually obtained from P. Wilkinson Containers Limited, London, and at the same time similar tins (125mm diameter x 125mm) were obtained for use as aggregate containers.

Prior to mixing the aggregate was heated to 165°C (table 11, B.S. 594) in an oven overnight, however, because the binder was not to be maintained at elevated temperatures for longer than 8 hours, a similar treatment was not possible. Several methods of bringing the binder to 160°C (table 11, B.S. 594) prior to mixing were considered. Firstly, it was possible to heat individual tins of binder, as required, using a hotplate such that the required temperature was attained immediately prior to mixing. This approach was considered too time consuming and prone to producing local overheating of the binder and was rejected. The use of an oven was considered the best solution, however, if not switched on until the morning when mixing was to take place, this operation was considerably delayed. The final solution, therefore, was to equip the oven with an automatic timer whereby it was switched on to allow just sufficient time for the binder to attain temperatures just prior to mixing.

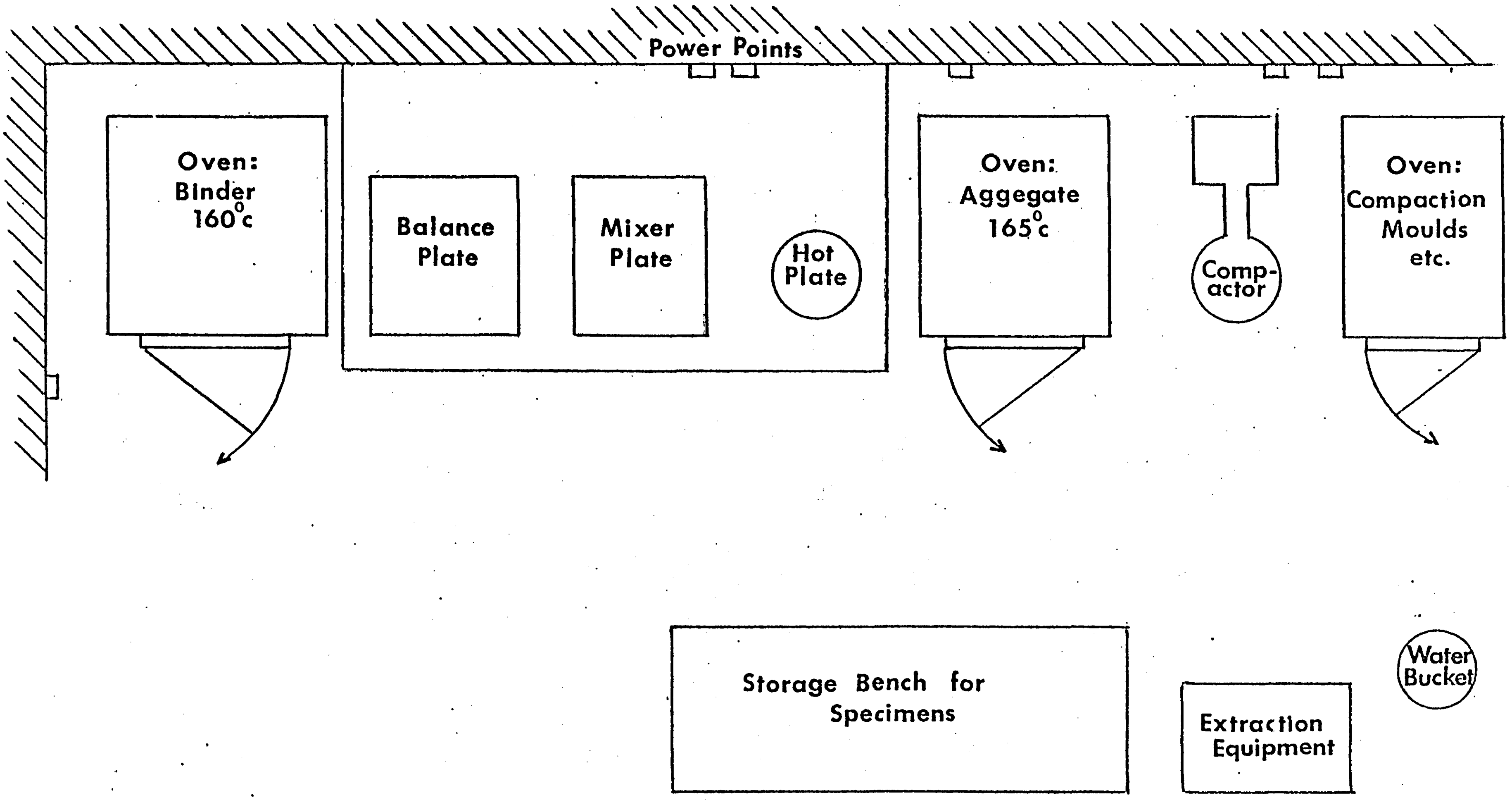
5.3.3 Mixing and Compaction

It was logical that these operations should be considered together. The aim being to develop an operating procedure, for the manufacture of 24 specimens, having the desired composition, in rapid succession whilst maintaining the temperature of the mixed material within the range 142-146^{o}C (table 11, B.S. 594) immediately prior to compaction.

Loss of heat during both operations was of considerable importance and in order to minimise this from the start, thought was given to the layout of equipment such that everything required at each stage was close at hand. The resulting layout is shown in figure 5.

To begin with, the mixing operation is important from the point of view of obtaining

1. the addition of the required amount of binder
2. a completely homogeneous mixture of constituents
3. the minimum of heat losses.

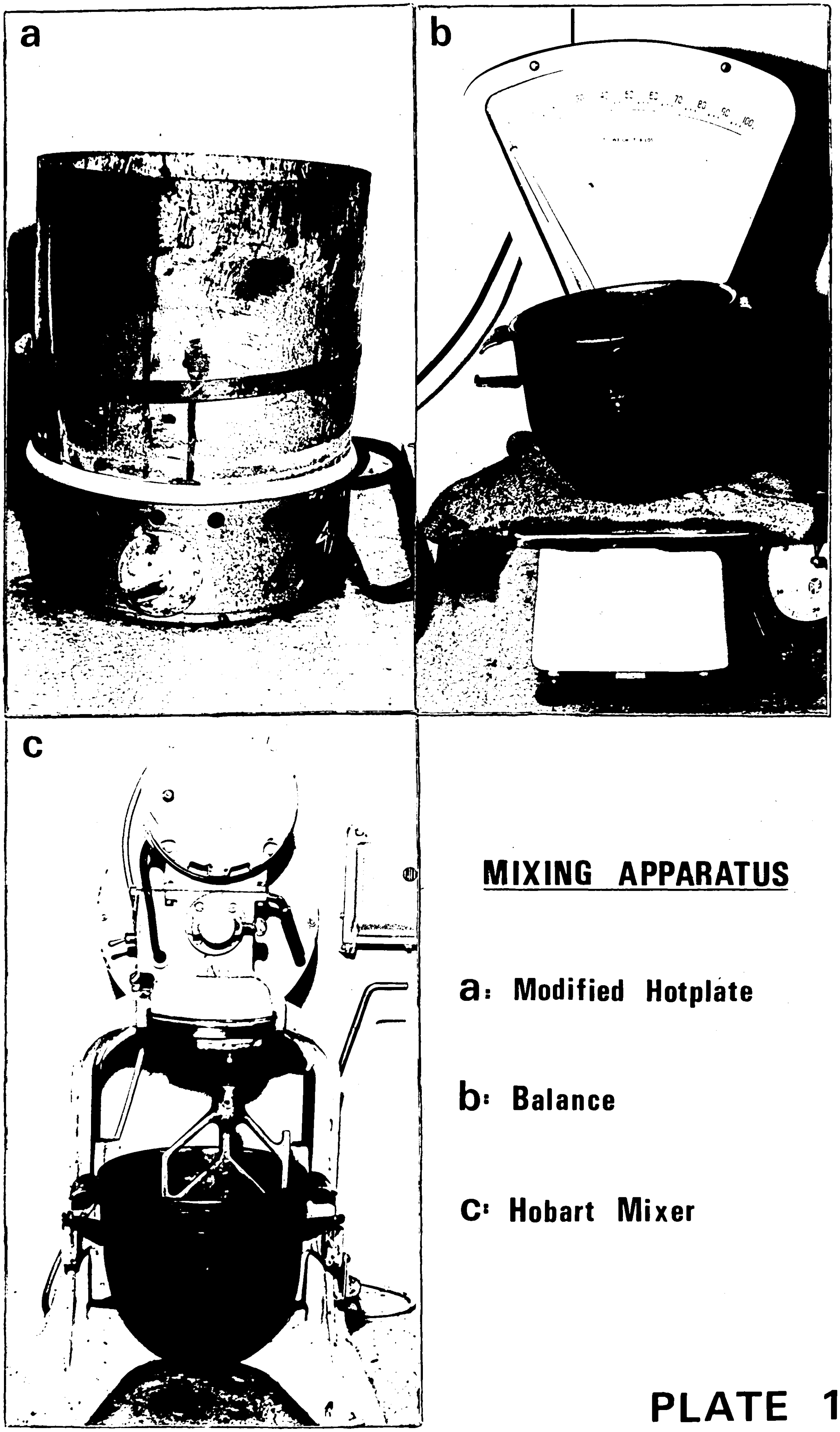


Layout of equipment for
Mixing – Compaction Operation

Fi

For this operation a mixing bowl fitted with a suitable heating element in order to maintain temperature, as recommended by B.S. 594, was not available. However, it was found possible to do without this by utilising a modified hotplate (plate 1a) into which the mixing bowl was placed whenever possible. In order to add the required amount of binder the mixing bowl containing the aggregate was placed on a 7 kg. capacity balance as shown in plate 1b. To reduce heat losses a heat resistant glove was first placed on the balance pan. The balance had previously been tared so that the pointer just registered on the scale when the bowl was positioned. Binder could then be poured into the bowl until sufficient, determined by reference to the scale, had been added to the nearest 0.5 gram.

The actual mixing operation was carried out using a ⅛ horsepower, 5 litre capacity Hobart food mixer (model no. CE100) see plate 1c. A smaller, less powerful mixer of similar make and capacity had been found to have insufficient power to complete the operation. Early work using a mixing paddle (plate 1c) proved unsatisfactory primarily due to its failure to make contact with the inside of the bowl. This resulted in material at the bottom remaining uncoated and a tendancy for binder to become stuck around the inside of the bowl. It was apparent that either modification of the paddle was necessary <u>or</u> that mixing by hand was needed at some stage to ensure all material became thoroughly mixed. The latter was considered too time consuming and likely to introduce an element of uncontrolled variability, and was rejected. Instead the paddle was replaced by a whisk. Unfortunately, the "standard" whisk for the mixer was unsuitable, having too many strands and not contacting the inside of the bowl. To overcome



MIXING APPARATUS

a: Modified Hotplate

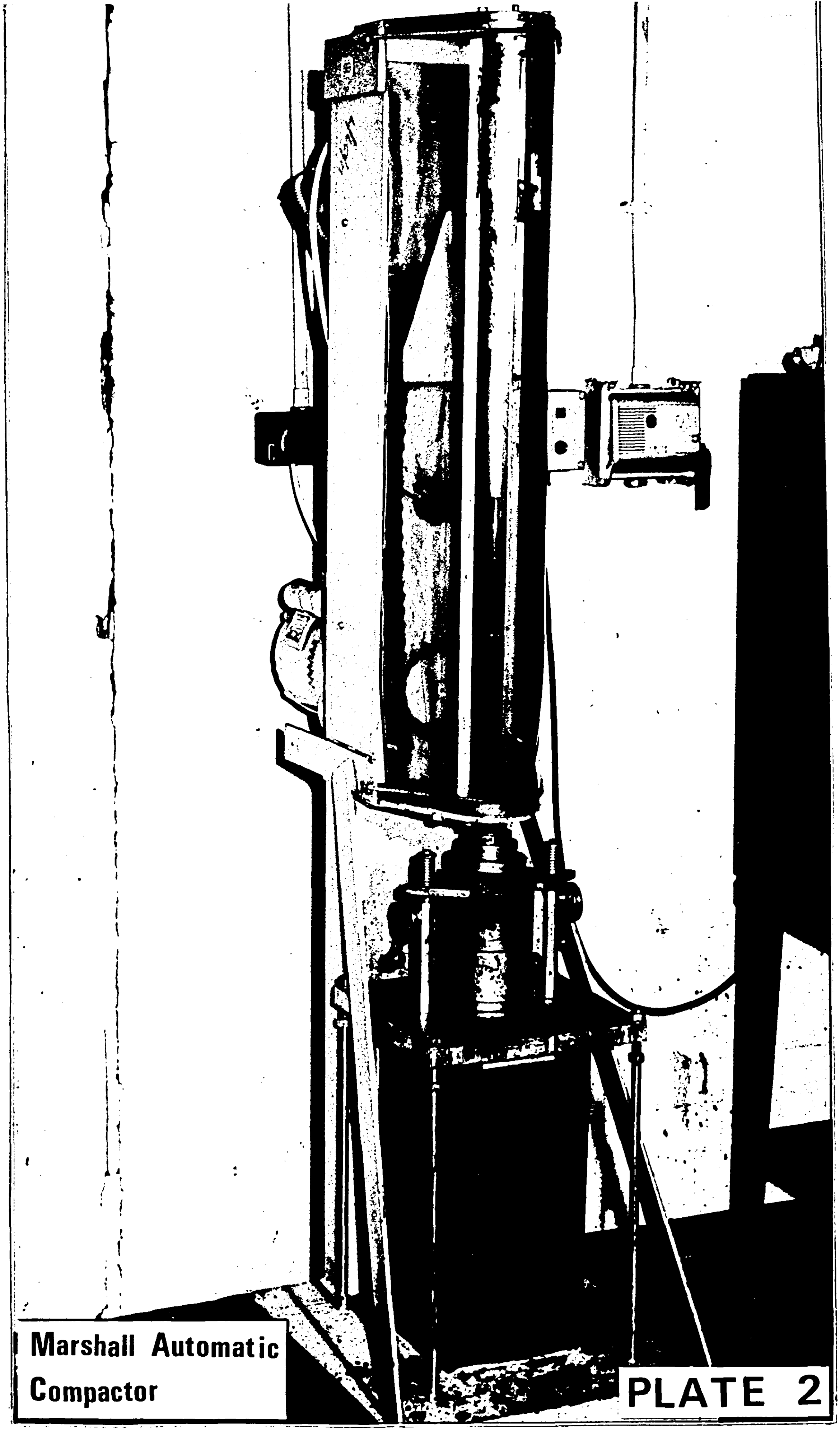
b: Balance

c: Hobart Mixer

PLATE 1

this the "standard" whisk was stripped down and re-built using 5 strands of 2 mm diameter stainless steel wire. Each strand was sufficiently long so it could be bent to the shape required in order for it to scrape to the bottom and inside of the bowl. Results discussed in Chapter 6 indicated that this solution combined with a mixing time of 1 minute at the intermediate speed setting produced a homogeneous mixture of the constituents. It also proved satisfactory for mixtures containing coarse aggregate, previously when a paddle was used, particles of coarse aggregate had become trapped and consequently crushed between it and the inside of the bowl. One drawback however was the tendancy for the wires to break frequently, and for this reason it was necessary to maintain a supply of wire to repair broken strands. For the same reason it was also advisable to have at least 2 whisks available for use at any one time.

When it came to specimen compaction, the equipment for both hand or automatic compaction was available. It was decided to utilise the automatic compactor (plate 2) in an attempt to remove the uncontrolled variation considered by the author to be inherent in the manual method. This apparatus was, therefore, checked to see that it complied with B.S. 594 in respect to mass of hammer, distance of fall and rate of delivery of blows. The former 2 requirements were met but it was found that it delivered blows at a rate of 45 per minute, not 60-70 per minute as required by B.S. 594. It was, therefore, necessary to modify the gearbox, such that blows were delivered at the required rate. In addition, the compaction moulds were checked to see that in particular their diameters were as specified in B.S. 594.



Marshall Automatic Compactor

PLATE 2

On completion of mixing, specimens were compacted (50 blows per face), extruded and prepared for testing next day according to B.S. 594 (3.4.2.5.), in addition each specimen was marked with appropriate identification number (4.6.3.) Immediately prior to compaction the temperature of the mixed material was determined. Using a mercury thermometer some delay was experienced as the mercury rose up the capillary, this could be reduced by maintaining the thermometer (when not in use) at a temperature of 140°C, by immersing it in an oil bath maintained at this temperature by means of a hot plate. However, the use of a Colmark electronic thermometer, giving an almost instantaneous reading, was found most practicable and this was used for all future temperature determinations.

The procedures developed for mixing and compaction succeeded in achieving the aims of firstly, maintaining the temperature of the mixed material within the range 142-146°C immediately prior to compaction, secondly, lead to the production of compacted specimens having the desired binder content and aggregate gradation, and finally, enabling 24 such specimens to be produced within the working day. In achieving this last aim, great advantage was found in employing the services of 2 operatives in order to spread the work-load, and this resulted in greater efficiency and consistence of operation. Assigning one operative to the mixing operation and the other to compaction, a great reduction in delay between the two operations was achieved. Benefit was also gained from the fact that both had less to think about and were less rushed, consequently less errors were made. It should be noted that in order to limit variation due to different operators, the roles were never reversed. With increased speed of operation, in order to maintain temperatures, it was essential that all equipment was immediately returned to the appropriate oven after use. It was also found advantageous to utilise 2 mixing bowls and 2 whisks, using each one alternately while the other was in the oven.

5.3.4 Measurement of Specimen Height

The average height (H) of compacted specimens was determined using the apparatus shown in figure 6. Consisting of a dial-gauge with a flat-foot attachment, held by an adjustable clamp arrangement above a smooth, flat, steel baseplate.

The apparatus was first calibrated by lowering the dial-gauge onto a machined steel block, 63.5 ± 0.1 mm high, placed on the baseplate directly beneath it, until a reading of approximately 1000 divisions was obtained. The dial-gauge was then firmly clamped in position, and the steel block was moved around beneath the foot. If the dial-gauge reading remained constant while this was done, no further adjustment was required. If the reading varied, adjustments were made until the above condition was achieved. The initial dial-gauge reading, corresponding to a specimen height - 63.5 mm, was then recorded.

Compacted specimens were in turn, placed on the baseplate beneath the foot of the dial-gauge, and the gauge reading recorded at 5 positions on the surface. If subsequent readings were greater than the initial reading, then the height at that point was greater than 63.5 mm and vice-versa. The height at each of the 5 positions was calculated and the average height (H) determined to the nearest 0.1 mm, as shown below:

Apparatus for Determination of Specimen Height

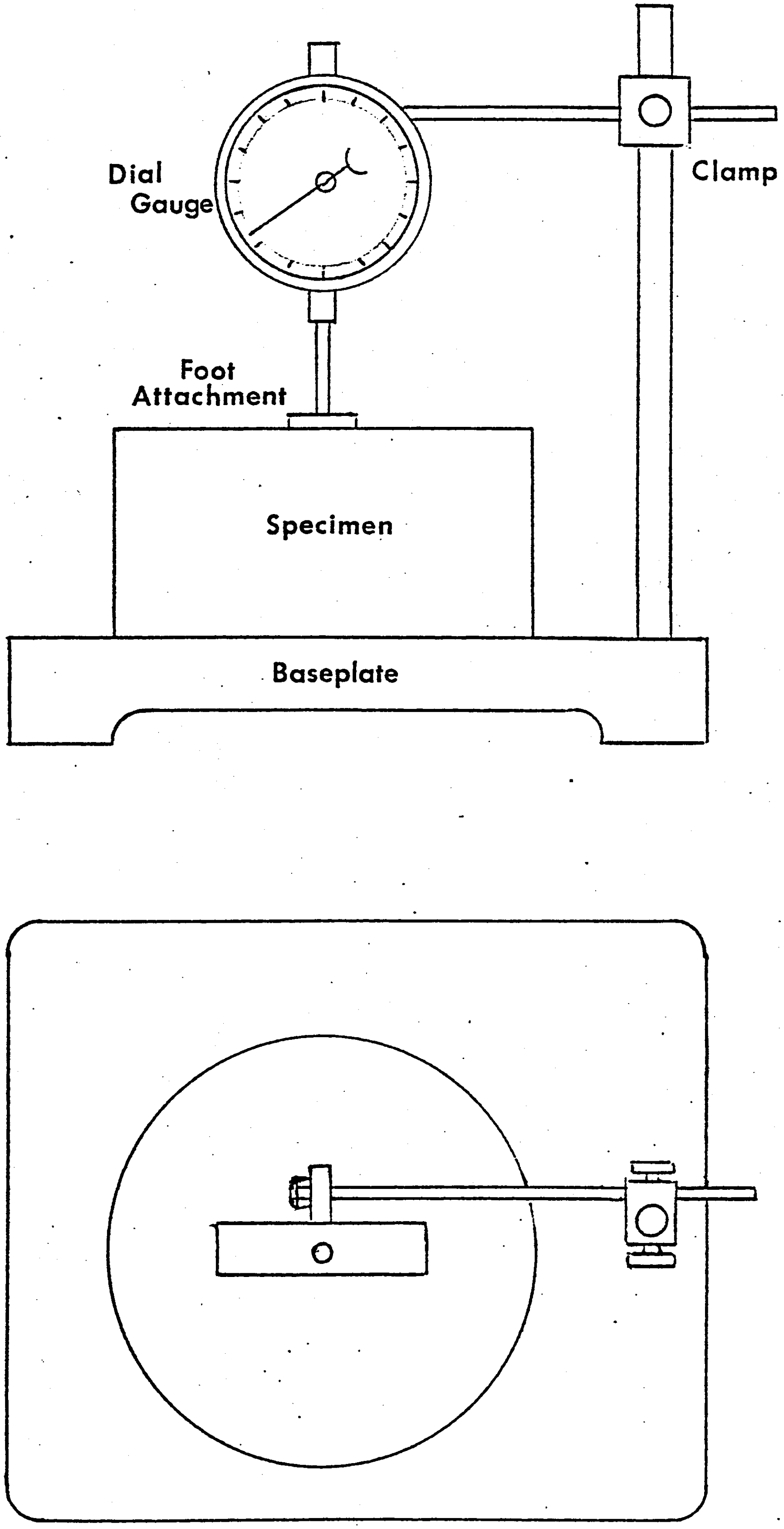


Fig. 6

Initial gauge reading = 1000 divisions

Each division = 0.01 mm

POSITION	GAUGE READING (divs)	GAUGE - INITIAL READING (divs)	(mm)	HEIGHT (mm)
1	1100	100	1.00	64.50
2	1095	95	0.95	64.45
3	1098	98	0.98	64.48
4	1102	102	1.02	64.52
5	1090	90	0.90	64.40
			Mean	64.47

report average height (H) as 64.5 mm.

Specimen heights were determined during the course of trial mixes (4.6.2.) but later this was omitted as it was found that specimen heights (as a result of trial mixes) were sufficiently close to the standard so as not to warrant this time consuming determination.

N.B. Stability corrections were, therefore, based on specimen volume (5.3.7.).

5.3.5 Determination of Specimen Density

To enable the determination of the Volume (B), Relative Density (S_M) and Compacted Aggregate Density (S_A) of each specimen, the following were determined to an accuracy of 0.1 gram.

Mass of dry specimen in air (W).

Mass of specimen immersed in water at $20 \pm 1^\circ C$ (W_W).

An Oertling electronic, digital balance of 2 kg capacity (model no. F22TD), with a facility whereby specimens could be weighed whilst suspended from beneath the balance, was found most suitable for this purpose. The formulae used in the calculations are given in table 21.

5.3.6 Calculation of Air Voids in Specimens

With a knowledge of the following:

(a) the percentages by mass of coarse aggregate, fine aggregate, filler and binder in each specimen (w_1, w_2, w_3 and w_B respectively).

(b) the relative densities of the coarse aggregate, fine aggregate, filler and binder used (S_1, S_2, S_3 and S_B respectively).

It was possible to calculate the Theoretical Maximum Relative Density (S_{TH}) of each specimen, (i.e. the relative density of a specimen containing zero air voids), and hence, the

Percentage Air Voids in the Mix (V_M)
Percentage Air Voids in the Mineral Aggregate (V_A)
Percentage Voids Filled with Binder (V_F).

N.B. Where the water absorption of the aggregate is 1% or greater, the mean between the Apparent Relative Density and the Relative Density on an oven-dry basis is used in the calculation of S_{TH}, otherwise Apparent Relative Density is used.

The formulae used in the calculation are given in table 21.

For a mixture comprised (as in 4.6.2.)

W_{ST}	=	0.0	grams	
W_S	=	780.2	grams	(Sand A)
W_F	=	124.8	grams	(Limestone dust)
W_B	=	95.0	grams	
Total W_M	=	1000.0	grams	

TABLE 21

Formulae used in Density - Voids Determinations

Specimen volume (B) = $W - W_W$ ml

Relative density (S_M) = W/B g/ml

Compacted Aggregate Density (S_A) = $S_M \times \frac{(100-w_B)}{100}$ g/ml

Theoretical Maximum Relative Density (S_{TH})

$$= \frac{100}{\frac{w_1}{S_1} + \frac{w_2}{S_2} + \frac{w_3}{S_3} + \frac{w_B}{S_B}} \quad \text{g/ml}$$

Percentage Air Voids in Mixture (V_M)

$$= \left(\frac{S_{TH} - S_M}{S_{TH}}\right) \times 100 \quad \%$$

Percentage Air Voids in the Mineral Aggregate (V_A)

$$= V_M + \left(\frac{w_B \times S_M}{S_B}\right) \quad \%$$

Percentage Air Voids Filled with Binder (V_F)

$$= \left(\frac{w_B \times S_M}{V_A \times S_B}\right) \times 100 \quad \%$$

the %age by mass of each constituent can be calculated

$$w_2 = \frac{780.2}{1000.0} \times 100 = 78.02\%$$

and likewise $w_3 = 12.48\%$ and $w_B = 9.5\%$.

If from weighings $W = 998.1$ grams

and $W_W = 472.0$ grams

then $B = 998.1 - 472.0 = 526.1$ ml

hence $S_M = \frac{998.1}{526.1} = 1.897$ glml

$$S_A = 1.897 \times \frac{(100 - 9.5)}{100} = 1.717 \quad \text{glml}$$

The relative densities of the constituents are (see 4.3.2., 4.4.2. and 4.5)

$S_2 = 2.62$ (Water Absorption = 1.4%, hence Relative Density used $= \frac{2.57 + 2.66}{2} = 2.62$)

$S_3 = 2.70$ and $S_B = 1.03$

hence $$S_{TH} = \frac{100}{\frac{78.02}{2.62} + \frac{12.48}{2.70} + \frac{9.5}{1.03}} = 2.292 \quad \text{glml}$$

and $$V_M = \frac{(2.292 - 1.897)}{(2.292)} \times 100 = 17.2 \%$$

$$V_A = 17.2 + \frac{(9.5 \times 1.897)}{(1.03)} = 34.7 \%$$

$$V_F = \frac{(9.5 \times 1.897)}{(34.7 \times 1.03)} \times 100 = 50.4 \%$$

5.3.7 Determination of Stability and Flow

The method of determination used in the past and favoured by B.S. 594 (1973) utilises an elastic proving ring inserted between the test head and the testing machine crosshead, to measure the force on the specimen, and a suitable dial-gauge mounted on (or held in contact with) the test head so as to enable the measurement of deformation. The necessity to determine the maximum force (Stability) and the deformation at maximum force (Flow) entails the simultaneous reading of two dial-gauges, at the instant maximum force is reached. Although the use of a proving ring fitted with a "dead-beat" dial-gauge facilitates accurate measurement of maximum force, when it comes to deciding when this is reached, and to making the subsequent deformation measurement, total reliance is placed upon human judgement and reaction. Further, if any results appear suspect, there is no record of the test other than the recorded gauge readings, and, therefore, no means of checking back. In the author's opinion these are areas where the accuracy and reliability of the method come into question. It was, therefore, decided to consider alternative methods of carrying out these determinations, with a view to obtaining increased simplicity, accuracy and reliability.

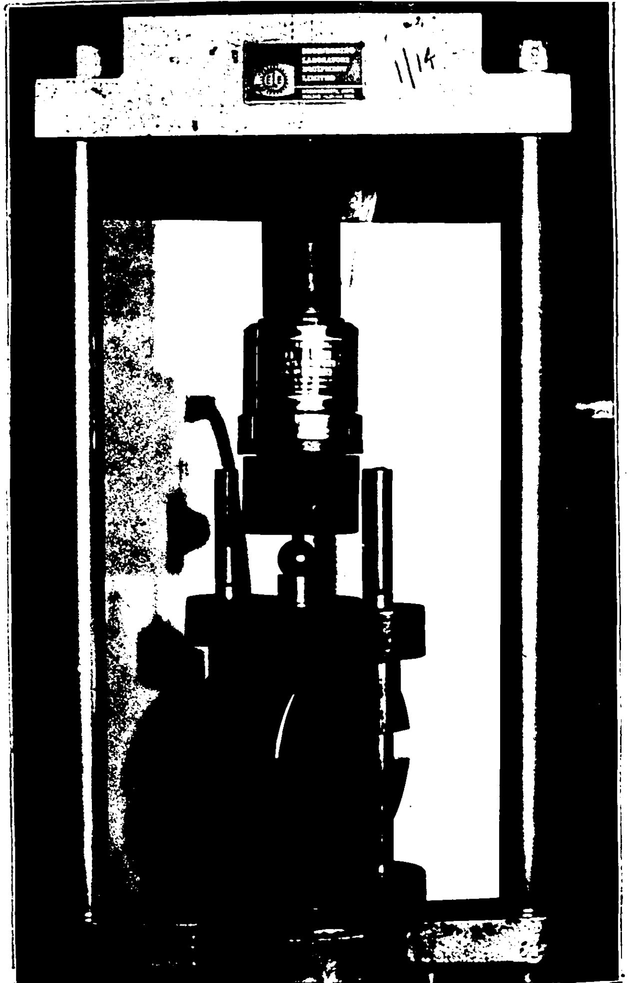
One such alternative was that used by Colebourn,(190) whereby, force and the corresponding deformation were measured continuously using a Load Cell and Displacement Transducer respectively. By feeding the output signals from each to an X - Y plotter a Force vs. Deformation curve was produced for each test. The point of maximum force is clearly defined on the graph, and once located, values of maximum force (Stability) and deformation at maximum force (Flow) can be accurately determined, knowing the calibration of the measuring devices. However, despite the increased accuracy, resulting from the removal of human factors and record obtained for each test, the author considers this system to be complex from the point of view of the electronics required and also envisaged problems associated with the setting up and zeroing of instruments, particularly the transducer, prior to each test. With a desire to reduce the complexity, this method was rejected in favour of that outlined below.

The system adopted (plate 3a), utilised a 5 ton (50kN) capacity NCB/MRE Compression Load Cell (Model No. 403),(191) supplied by W. H. Mayes and Son (Windsor) Limited, to measure continuously the force being applied to the specimen. This was powered by a 10 volt D.C. stabilised, input voltage supply and the output was connected to a single pen Rikadenki Chart Recorder (model no. B18H),(192) supplied by T.E.M. Sale Limited, Crawley. Both input and output connections were made via the same lead and 6 pin connector. To facilitate measurement, the Load Cell was rigidly held between the testing machine crosshead and the test head by means of the assembly shown in figure 7. As the test head is driven against this assembly, the force exerted is measured by the Load Cell and a Force vs. Time curve produced by the Chart Recorder (see figure 8). The insertion of a 20 mm diameter, ball bearing between the testhead and the lower locating plate of the support assembly, ensured that force was transferred to the Load Cell without eccentricity. The Chart Recorder was calibrated such that a full scale deflection (f.s.d.) on the vertical scale of the chart, corresponded to maximum output voltage from the Load Cell, in turn corresponding to an applied force of 50, 25 or 12.5 kN, as required.

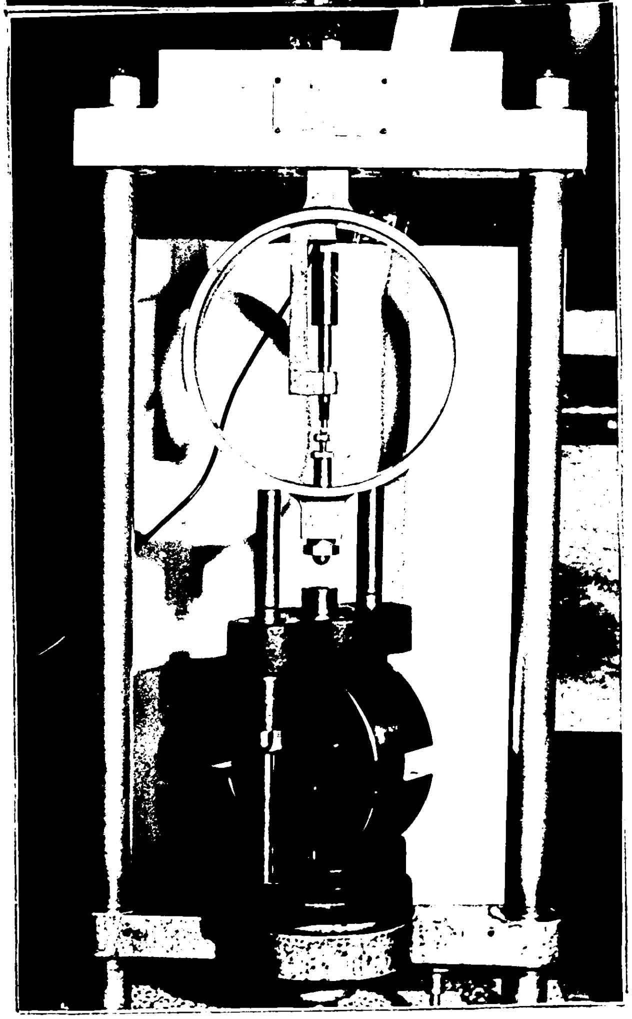
N.B. The procedure for calibrating the recorder, including a wiring diagram is given in Appendix B.

The instant of maximum force is clearly defined on the chart and the value of maximum force is calculated as follows:

Marshall Test Apparatus



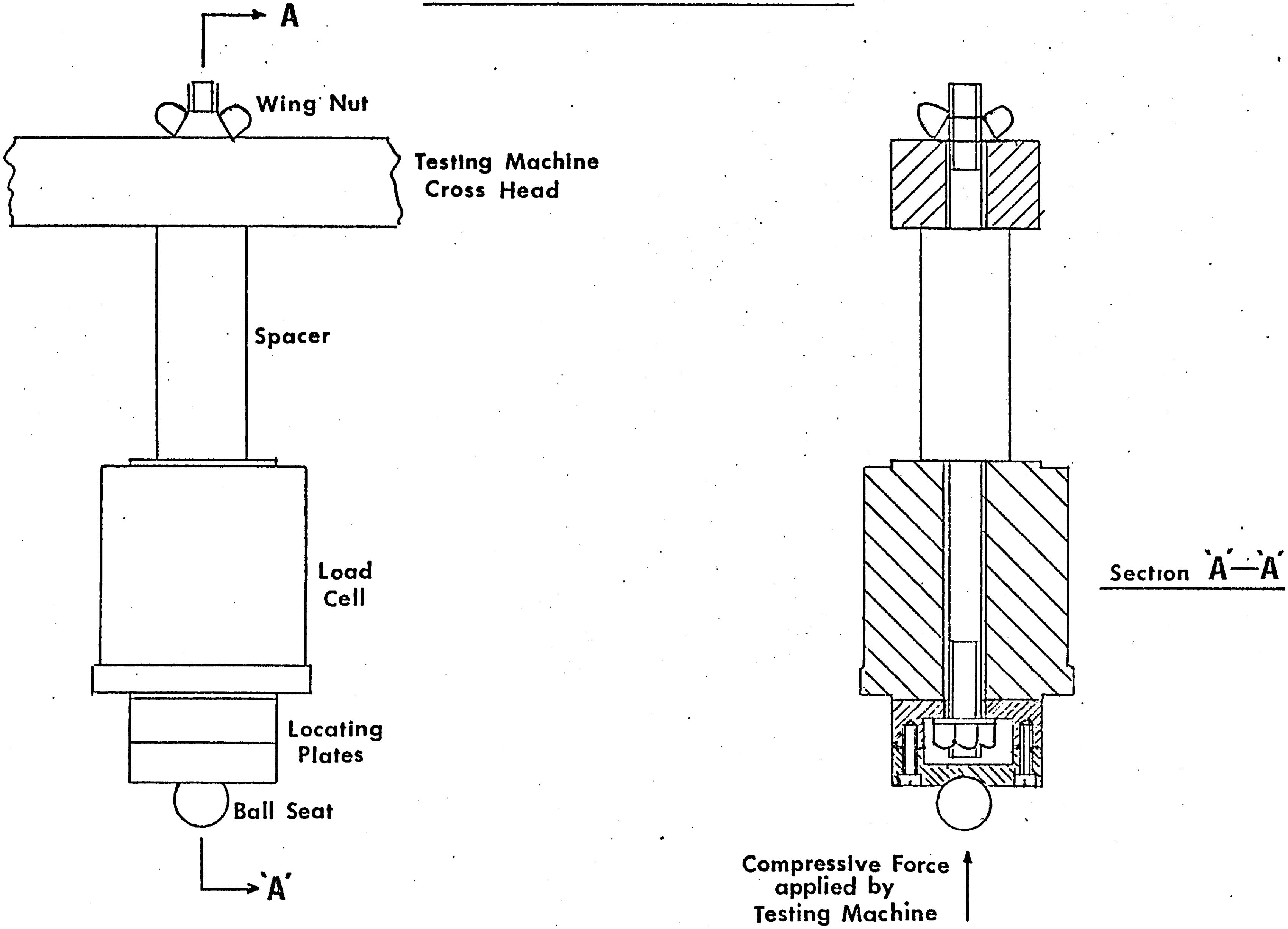
a: Load Cell



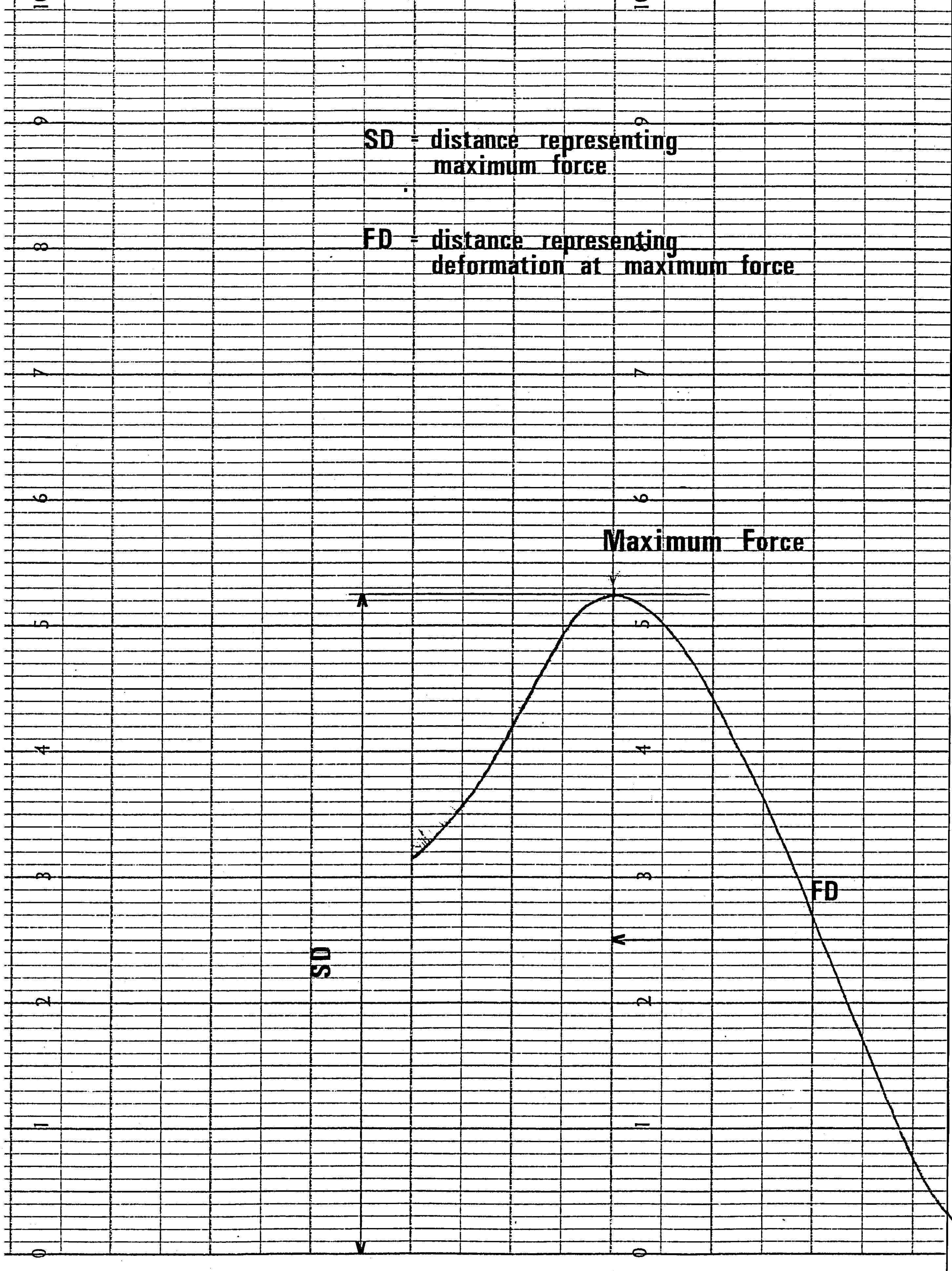
b: Load Ring

PLATE 3

Load Cell Support Assembly



Fi


SD = distance representing maximum force
FD = distance representing deformation at maximum force
Maximum Force
SD
FD
0
1
2
3
4
5
6
7
8
9
10

Recorder calibrated such that f.s.d. = 12.5 kN

i.e. 1 inch on chart = 1.25 kN

Distance representing maximum force (SD), see figure 8

= 5.25 inches (estimate second decimal place)

hence Maximum force (measured stability)

= 5.25 x 1.25 = 6.56 kN.

A correction is then made for variation in specimen volume, in accordance with table 12, B.S. 594.

If volume (B) = 525.9 ml

correction factor (table 12, B.S. 594) = 0.97

hence Corrected Stability (S) = 0.97 x 6.56 = 6.36 kN.

Assuming that the testing machine applies load at a constant-rate of strain of 50.8 mm/min, then when a chart speed of 60 cm/min is used, each cm on the chart (horizontal scale) represents (50.8 ÷ 60), 0.847 mm of ram movement. As the Load Cell is almost totally stiff, this ram movement is equivalent to deformation of the specimen alone, and it is, therefore, possible to determine the Flow value from a chart recording produced under such conditions, as follows.

Distance from the point where the curve leaves the zero-line of the chart to a position corresponding to maximum force (FD), see figure 8 = 8.54 cm (estimate second decimal place)

hence Flow (F) = 8.54 x 0.847 = 7.2 mm.

This method of determining Flow relies on the fact that the testing machine applies load at a known, constant-rate of strain and that the chart moves at a known, constant rate. It was, therefore, necessary to ascertain if this was the case. The chart speed was determined by timing its movement over several 10 second periods and the average was compared with the speed setting on the recorder. The speed determined in this manner was found to be 60 cm/min and constant. The loading rate was determined by firmly clamping a dial-gauge in contact with the ram of the testing machine and recording the distance moved with respect to time. An initial period of "machine take-up" after switching on was discovered, but after about 2 seconds the ram was found to move at a constant rate, several readings indicated this to be 50.8 mm/min (±0.2 mm/min, ±0.4%). Repeating this procedure whilst testing a specimen, indicated that the loading-rate remained unchanged and constant during this operation. This being so, the author considered the previously described method as being valid for the determination of Flow.

N.B. A gap of about 3 - 4 mm was left between the ball bearing and the lower locating plate on commencement of testing, thus allowing for "machine take-up" prior to any recording being made.

This testing procedure was developed to enable the testing of 24 specimens, and apart from the test method itself, the determinations were made in accordance with B.S. 594, section 3.4.2.8. In addition, to Stability and Flow, a parameter referred to as Marshall Quotient (Q) was also calculated as follows:

$$\text{Marshall Quotient (Q)} = \frac{\text{Corrected Stability}}{\text{Flow}}$$

$$= \frac{6.36}{7.2} = 0.88 \text{ kN/mm.}$$

A variation on the method described was used in part of the investigation (see chapter 6), this involved replacing the Load Cell with a 10 kN capacity Load Ring,(193) fitted with a Displacement Transducer,(194) supplied by Sangamo Western Controls Limited (plate 3b). As force was applied to the specimen the deformation of the Load Ring was measured continuously by the transducer whose output signal was fed to the Chart Recorder. Knowing the calibration of the Load Ring and Transducer, the trace produced what could be interpreted as a Force vs. Time curve, and Stability could be calculated as for the Load Cell system.

In determining Flow, it must be remembered, that in applying the same techniques as before, part of the total deformation measured is due to the deformation of the Load Ring. However, knowing the calibration of the Load Ring and the maximum force, it is possible to calculate the amount of Ring deformation and subtract it from the total deformation to obtain Flow.

5.3.8 General Considerations

The reliability of the manufacturing and testing procedures, depends to a great extent on the equipment used, and it, was therefore, considered necessary to carry out periodic checks on the following:

Balances
Oven and waterbath temperature controls
Compactor - height of drop, rate of blows, counter*
Load Cell calibration
Testing machine - loading rate*
Recorder - chart speed*

* it was considered desirable and feasible to check these prior to each test run.

When it came to carrying out Marshall Tests at E.R.C.A. it was considered desirable, from the point of view of reproducibility, to duplicate as far as possible the equipment and operating procedures used in Sheffield. In particular, duplication of the following was considered essential:

Compaction Moulds
Compactor
Measuring system - Load Cell and Chart Recorder.
Operating procedures (see figure B.1.2. Appendix B).
and was successfully accomplished.

In order to speed up the calculation of specimen properties and to remove errors, a computer program (MARSHL) was written for this purpose. Full details of this, including sample printout are given in Appendix A.

5.4 The Indirect-Tensile Test

5.4.1 Introduction:

At the onset of this investigation, no recognised, standard test method for the determination of the Indirect-Tensile Strength of Bituminous mixtures existed and it was, therefore, necessary to develop equipment and procedures to facilitate this. In doing so, reference was first made to the literature (2.2.3), which indicated that several methods (table 9) had been successfully applied to this end in the past. Of the available information, that originating from the Center for Highway Research, University of Texas at Austin was considered by the author to be of most use. In particular, results reported by Hudson and Kennedy,(98)(104) concerning the application of this test method to Asphaltic Concrete and including an evaluation of certain factors (mentioned in 2.2.5) which were shown to have an effect upon the results obtained were of greatest assistance. With a desire to exclude any similar programme of evaluation from the present investigation, on the grounds of the time involved, it was decided to develop a testing procedure based upon the recommendations of Hudson and Kennedy.(98)(104) These recommendations were as follows:

1. Specimen size should be as large as possible.
2. Steel loading strips should be used.
3. 25 mm (1 inch) wide loading strips should be used.
4. Loading rate of 50.8 mm/min (2 in/min) to be used.
5. Test temperature 24 - 25°C, to be used.

5.4.2 Test Specimens:

As mentioned previously (2.2.5.3), from the point of view of reducing the scatter of individual test results about the mean value, it is desirable to use specimens that are as large as practicable, with 152.4 mm dia x 203.2 mm long (6 in x 8 in) being suggested as suitable.(98) However, having given this due consideration, the author decided to use smaller specimens, 101.6 mm dia x 63.5 mm (4 in x 2.5 in), compacted using the Marshall automatic compactor (50 blows per face), for the following reasons:

1. The equipment required was already available.
2. An efficient operating procedure for mixing and compaction had already been developed.
3. The use of larger specimens would entail the development of alternative compaction equipment and procedures.
4. Marshall specimens had been successfully used and indeed favoured by other workers(39)(64)(98)(102)(103)(115) in the past.
5. The most important consideration however was the intention to correlate Marshall and Indirect-tensile test results.

By using identical mixing and compaction procedures for both tests, the resulting specimens (of given composition), tested by both methods should be nominally identical from the point of view of density, particle orientation, etc, thus facilitating a direct comparison between the results obtained with test method being the only variable.

For the purposes of this investigation, therefore, the constituent materials were prepared, mixed and compacted into test specimens using the procedures developed during initial work with the Marshall test, see 5.3.2 and 5.3.3. The height (H) of each compacted specimen was determined using the method described in 5.3.4, and determinations made to enable the calculation of the density and air void content of each specimen, see 5.3.5.

5.4.3 Determination of Indirect-Tensile Strength:

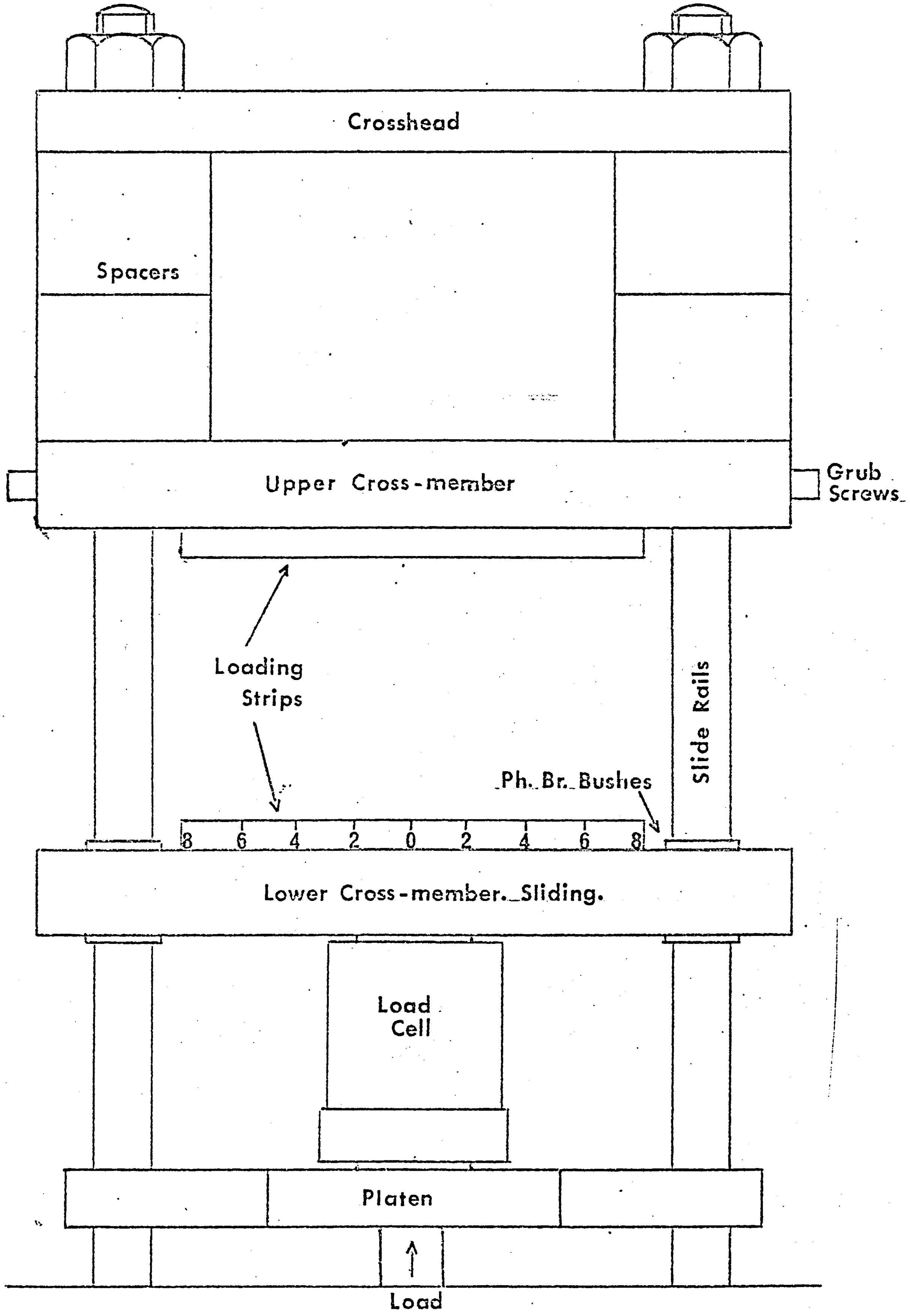
In the absence of any suitable alternative it was found necessary to use the Marshall testing machine to apply load to specimens under test, in doing so the recommended loading rate of 50.8 mm/min was achieved. However, in using this equipment, certain major modifications were required to permit the application of load to specimens via 25 mm wide, steel loading strips which remained essentially parallel during testing. In designing these modifications, several other factors had to be considered at the same time:-

1. The requirement to measure the force exerted on the specimen at failure and the vertical deformation undergone by the specimen at failure.
2. The recording equipment available to facilitate such measurements.
3. The size of specimens, initially 101.6 mm dia x 63.5 mm, but later the use of larger specimens (152.4 mm dia) was envisaged.
4. The requirement to locate specimens centrally prior to test.
5. Test temperature.

Initial consideration was given to modifying the Marshall testhead, replacing the curved jaws by a system supporting the loading strips and allowing the upper strip to move in the same way as the upper jaw of the original testhead. With the specimen in place, testing and recording could then be accomplished in the same manner as that developed for the Marshall test. This solution was, however, rejected for a number of reasons, including anticipated difficulties in centering specimens prior to test and problems in extending the method to specimens larger than 101.6 mm dia.

After careful consideration, the final design outlined below was chosen. Modifications were made to the testing machine itself, thus enabling a rigid system to be designed, whilst providing ample room to permit the centering of specimens prior to test, and allowing for larger specimens to be accommodated. The modified equipment is illustrated in figure 9 and plate 4 (a).

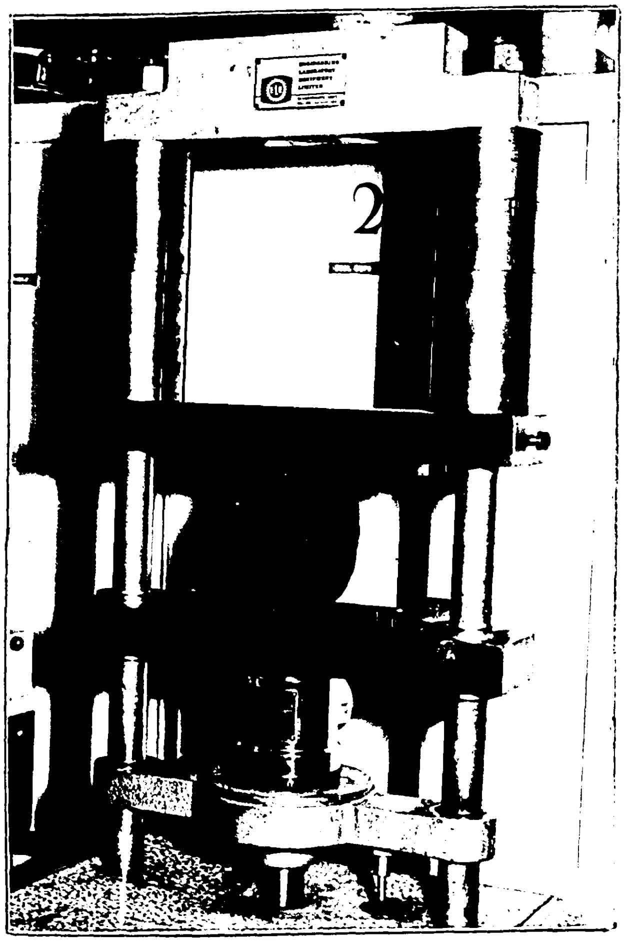
The steel loading strips, 25 mm wide x 12 mm deep are supported centrally on two rigid, steel cross-members, provided with suitable holes to allow them to slide over the vertical supports of the testing machine. The upper cross-member is clamped firmly in position by means of 2 grub screws. To ensure this member remains rigid during testing, steel spacers are placed over the vertical testing machine supports, between this member and the upper cross-head of the testing machine, the number of spacers used depends on the diameter of the specimen under test. The lower cross-member is provided with phosphor-bronze bushes to permit it to move without "friction" up and down the vertical supports of the testing machine. Inserted between this member and the testing machine platern is a load cell located by means of a screw which stands proud of the platern and locates itself in the base of the load cell. The load cell is connected via a lead to a stabilised voltage supply, digital voltmeter and chart recorder, all of which are as described in relation to the Marshall test, and all are connected and calibrated in the same way.



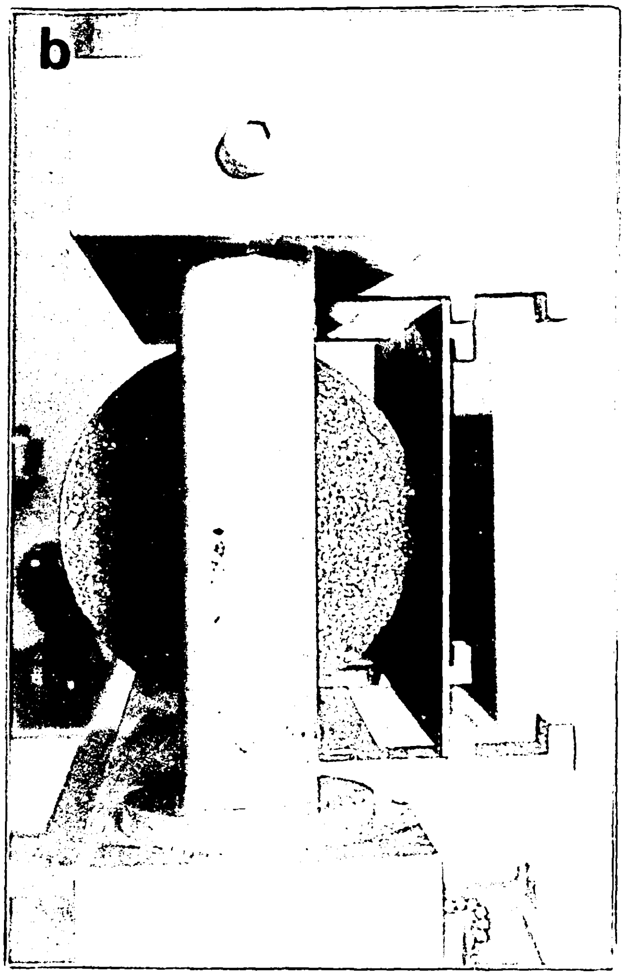
Indirect-Tensile Test Rig

Fig. 9

INDIRECT - TENSILE TEST APPARATUS



a : Testing Frame



b : Centring of Specimen

PLATE 4

In order to centre specimens prior to test, numbers are provided on the lower loading strip, (zero at the centre, increasing outwards at ½ inch intervals), and by referring to these, specimens can be located centrally with respect to this scale. To facilitate centring in a direction perpendicular to this, the system illustrated in plate 4(b) was used. A suitably dimensioned support and backstop arrangement was provided on both the upper and lower cross-members such that when the steel centring plate was inserted and positioned against the backstops, and a specimen held in contact with it (as in plate 4 b), the specimen was then central with respect to the loading strips. The arrangement allows for the plate to remain in position until load is being taken by the specimen, at which point, it can be removed. Thus centring can be achieved whilst leaving a small gap between the specimen and the upper loading strip, thus allowing sufficient time for machine take-up to occur prior to any recording being made, (as in the Marshall test).

Prior to test, specimens were brought to a temperature of 25°C by placing them in a thermostatically controlled water-bath for at least 45 minutes. Using the set-up previously described, it is not possible to bring any of the equipment to test temperature prior to testing. However, as the test temperature (25°C) was only slightly above normal room temperature, the author considered this to be unnecessary provided testing was carried out as quickly as possible.

Having previously calibrated the recording equipment (see Appendix B), each specimen was in turn centred between the loading strips, leaving a gap of approximately 4 mm between the specimen and the upper loading strip. The testing machine was switched on, and as soon as load was being taken by the specimen, the centring plate was removed. The force being exerted was measured continuously by the load cell and a Force vs. Time graph produced by the chart recorder. When the specimen failed, the testing machine was switched off, the specimen unloaded and the operations repeated as quickly as possible until all specimens had been tested.

A typical Force vs. Time graph is shown in figure 10. Knowing the calibration of the equipment, the force at failure can be determined in the same manner as in the Marshall test.

Calibrated for full scale deflection = 12.5 kN

1 in on chart = 1.25 kN

Distance on chart representing maximum force (SD)
= 6.55 inches (see figure 10)

Maximum force(P) = 1.25 x 6.55 = 8.19 kN

hence, knowing the dimensions of the specimen, the Indirect-Tensile Strength (I.T.S.) can be calculated:

Diameter (D) = 101.6 mm

Height (H) = 63.2 mm

$$\text{I.T.S.} = \frac{2P}{\pi DH} = \frac{2 \times 8.19 \times 10^3}{3.142 \times 101.6 \times 63.2} = 0.812 \text{ N/mm}^2$$

The vertical deformation undergone by the specimen at failure (ΔD) was determined from the chart recording, in a manner identical to that by which Marshall Flow was determined, i.e. assuming a constant rate of ram movement (50.8 mm/min), a constant rate of

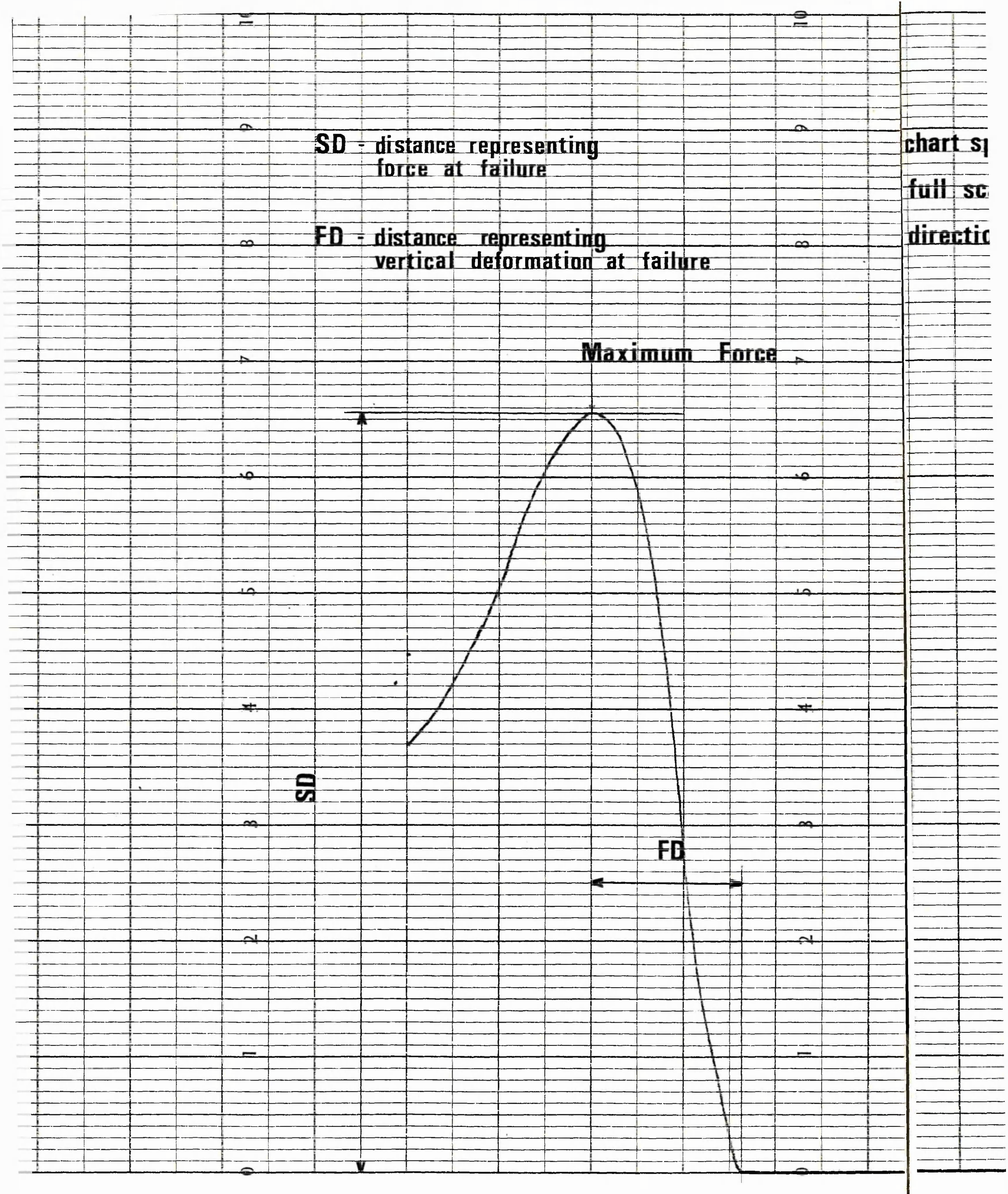

SD - distance representing force at failure
FD - distance representing vertical deformation at failure
Maximum Force
SD
FD
10
9
8
7
6
5
4
3
2
1
0
chart s
full sc
directic

chart movement (60 cm/min) and that <u>all</u> deformation is that occurring within the specimen, then 1 cm of horizontal chart movement corresponds to 0.847 mm of vertical deformation of the specimen, then:

Distance representing deformation at maximum force (FD)

= 3.25 cm (see figure 10)

Vertical deformation at failure (ΔD) = 0.847 x 3.25 = 2.8 mm

Also determined was a parameter referred to by the author as Tensile Quotient (T), which after Francken,(118) is defined as the ratio of horizontal tensile stress (I.T.S.) to vertical diametral strain ($\Delta D/D$) over the same diametral plane at failure:

$$= \frac{2P}{\pi \Delta D H} = \frac{2x8.19x10^3}{3.142x2.8x63.2} = 29.5\ \mathrm{N/mm^2}$$

To assist with calculations a computer program (SPLIT) was written and used for this purpose, full details and sample output are given in Appendix A.

5.5 The Wheel-Tracking Test

5.5.1 Introduction

It was necessary to design from scratch the equipment required to compact and test specimens by this method. Initial reference was made to the literature (2.2.4), but during the early formulation of a design most assistance was gained from visits to 2 establishments having operational facilities of this kind, to T.R.R.L. where the original test(1) of this type was developed, and to SHELL, Thornton Research Centre, whose Asphalt Compaction and Trading (A.C.T.) machine(43) was a more recent development of the original design. Based upon the information gained from seeing and discussing these pieces of equipment, the following design criteria were established:

1. The aim was to develop a single machine, capable of compacting and testing specimens, 305 x 305 x 50 mm in size, similar in nature to the A.C.T. machine. The author considered it desirable from a practical point of view to concentrate effort on a single piece of equipment rather than divide attention by developing separate machines for compaction and testing.
2. The machine was to be operated by a hydraulic system as this was considered necessary in order to cope with the high applied loads, particularly during the compaction operation.
3. The machine was to be housed in a self-contained, insulated cabinet with a facility to control the temperature of the interior during testing.
4. Recording of the rut depth during the test was to be continuous and accomplished by means of a displacement transducer and chart recorder set up.
5. The test conditions were to be those used by T.R.R.L., namely:

Solid-rubber tyred wheel, 203.8 mm dia x 50.8 mm wide,
hardness = 80 (Dunlop scale), as used in the Immersion Wheel
Tracking test.(1)
Load on wheel = 525 N producing
Contact stress = 520 - 560 kN/m^2
Distance of travel = 250 mm
Speed = 42 passes per minute
Temperature = 45°C.

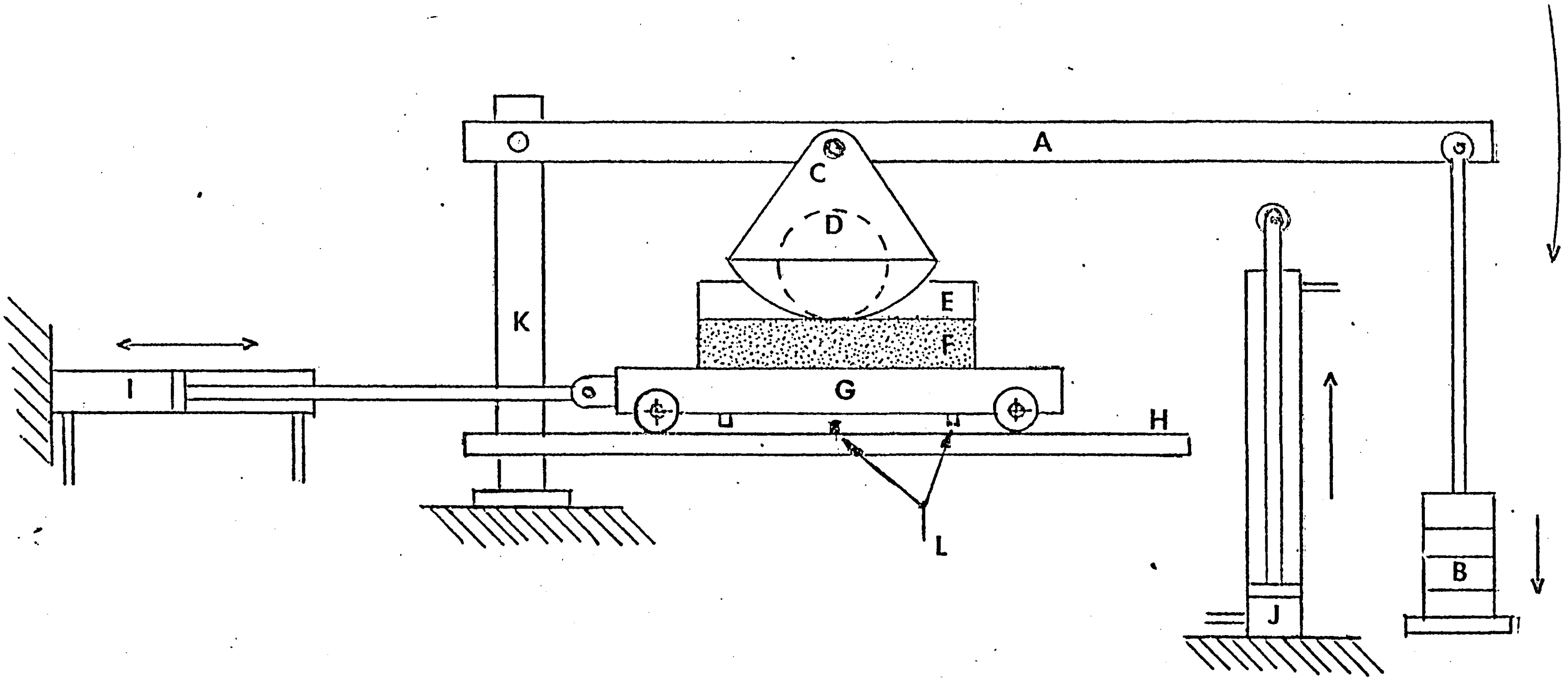
It was, however, considered desirable to have the facility to vary the above conditions and, therefore, the final design was required to incorporate the ability to do so.

5.5.2 Description of Apparatus:

The final design, based to a large extent upon the SHELL A.C.T. machine, but incorporating considerable modification and refinement, is shown in figure 11 and plate 5.

The essential features are; a 305 mm square, steel mould, bolted to a 12 mm thick steel table, as a means of providing all-round support for specimens at all times. The mould itself is a 4 piece assembly, held together by bolts, allowing it to be quickly and easily dismantled to facilitate the removal and positioning of compacted specimens. A similar 4 piece extension assembly can be bolted to the top of the mould for the compaction operation, providing the extra volume needed to contain the uncompacted mixture and also act as a guide to keep the roller segment in position.

The table supporting the mould is provided with 4 wheels which

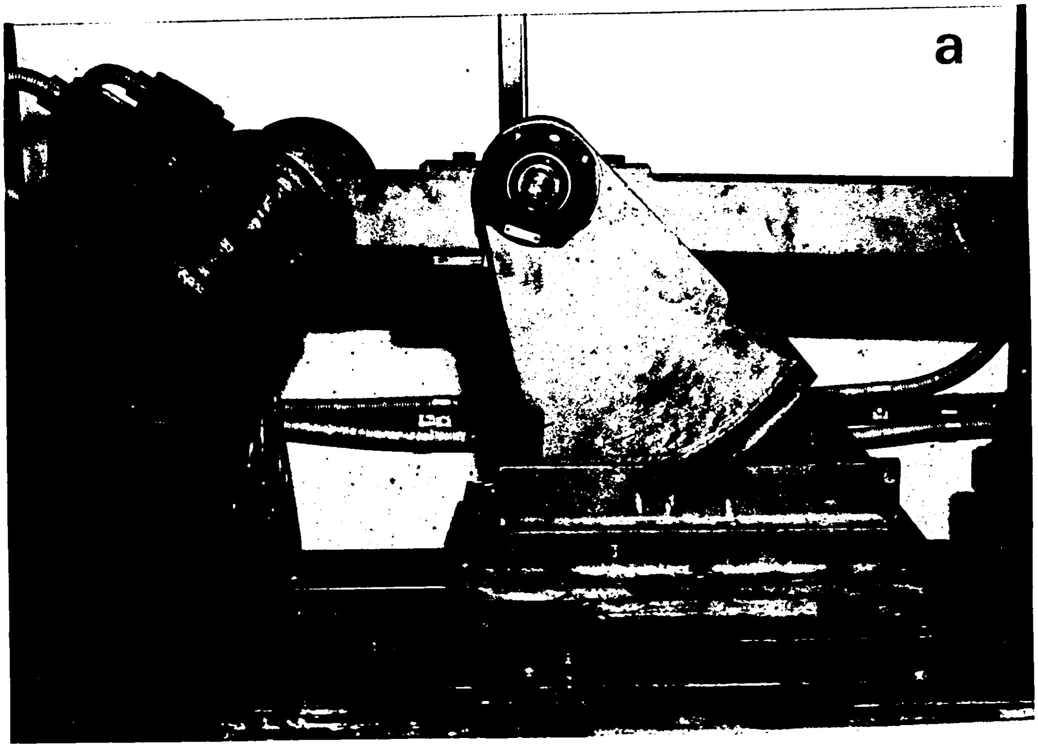


A	Loading Beam	G	Carriage
B	Load Weights	H	Rails
C	Segmental Roller	I	Cylinder. Reciprocating
D	Tracking Wheel	J	" . Lifting
E	Mould Box Extension	K	Support
F	Specimen	L	Stroke Adjustment

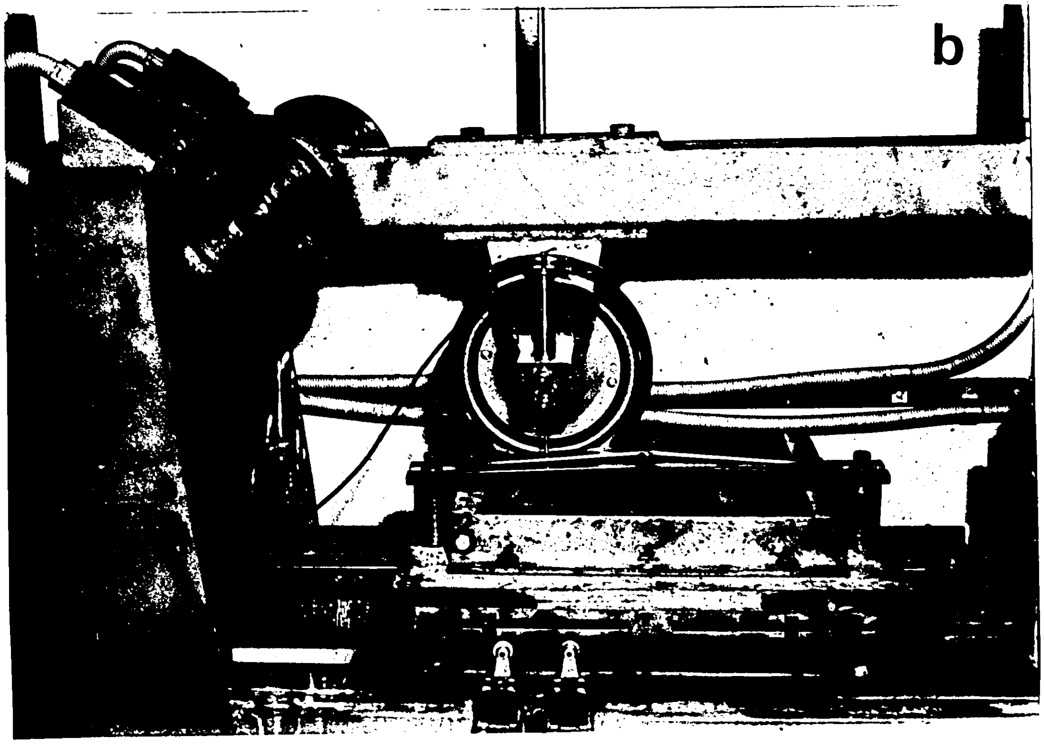
Schematic Arrangement of

Roller-Compactor / Wheel-Tracking Machine

Fig. 11



a : Compaction



b : Tracking

WHEEL - TRACKING MACHINE **PLATE 5**

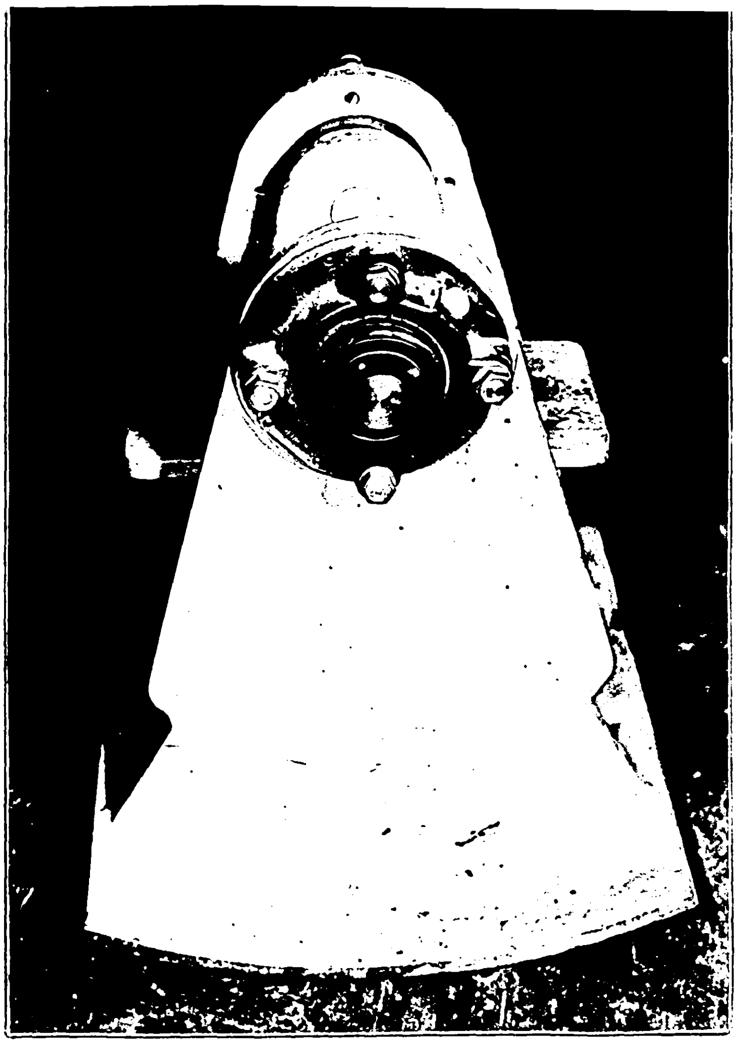
run on rails located on top of the main frame of the machine. The latter is constructed of steel sections welded together and bolted to the floor to provide a rigid working platform at a comfortable working height. The table itself can be driven to-and-fro by means of a hydraulic cylinder, fastened to its underside, and the speed of travel can be adjusted to suit requirements. The distance of travel is determined by limit switches fastened to the main frame, and "knock-offs" attached to the table, this arrangement is shown clearly in plate 5b. By adjusting the position of the "knock-offs" the distance of travel can be adjusted as required.

The main loading beam, comprised of a length of hollow steel section, is supported at one end by 2 bearings which allow it to pivot about this fixed end. The other end of the beam is provided with a hanger arrangement on which masses can be placed to provide the load required to achieve compaction. The loading beam can be raised or lowered by means of a hydraulic ram positioned vertically on the main frame.

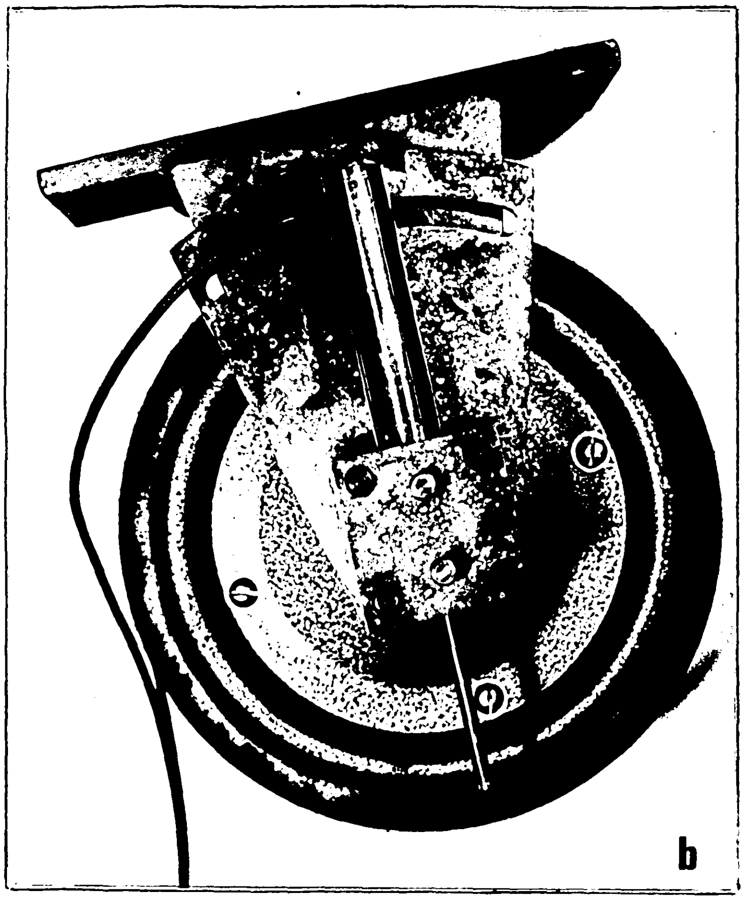
Either the roller segment (plate 6a) or solid-rubber tyred wheel (plate 6b) required for compaction and testing respectively can be attached to the loading beam by means of 2 bolts as required. The roller segment is provided with a pair of bearings such that it can freely rotate about its position on the beam and the wheel is provided with a mounting for a displacement transducer, which facilitates the measurement of rut depth.

The Wheel-Tracking machine is enclosed within a specially constructed

WHEEL - TRACKING TEST



a: Roller Segment



b: Wheel and Transducer

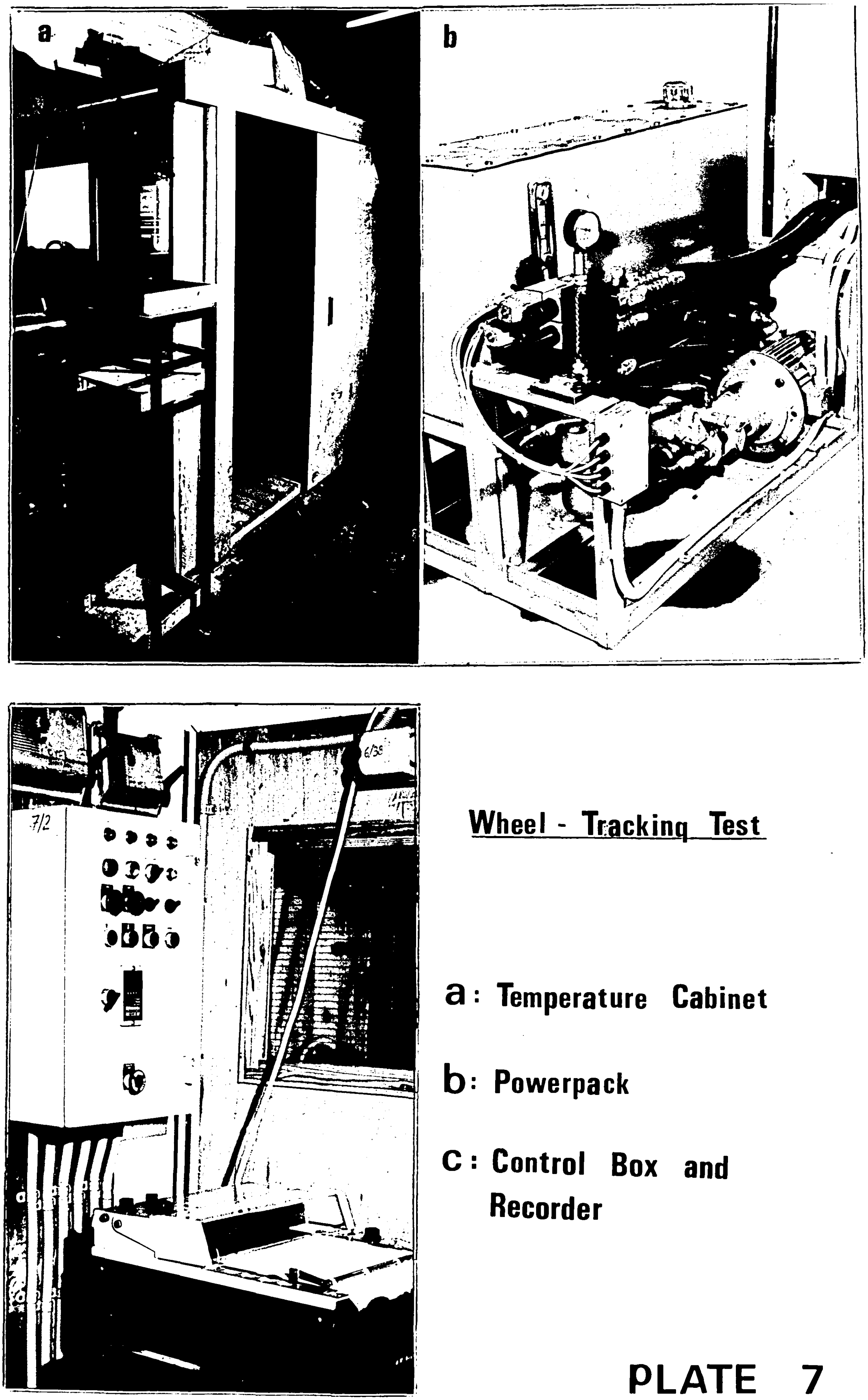
PLATE 6

temperature cabinet (plate 7a). This is approximately 2 m long x 1.5 m wide x 2 m high, comprised of a metal framework (25 mm square "speed-frame"), the outside of which is clad with 25 mm thick sheets of insulating material (20 mm of polystyrene backed with 5 mm of plaster board) and the exterior is faced with 3 mm thick plywood, all such material had been treated to resist fire. The cabinet is in addition provided with a wooden floor, sliding door, observation window and an electric light.

Heating is achieved using a 1.5 kW industrial fan heater mounted on the wall and the air in the cabinet is circulated to ensure a relatively uniform distribution of temperature. To facilitate this, air is removed at the top of the cabinet by an electric pump, circulated through a length of 150 mm dia plastic pipe and returned to the bottom of the cabinet. The temperature is thermostatically controlled such that the required temperature is maintained at the working height of the machine. For the purposes of this investigation this was 45 ± 1°C, but the equipment was found capable of maintaining temperatures up to 60°C.

The mains electricity supply, hydraulic power-pack (plate 7b) and recording equipment (plate 7c) are all external to the cabinet. Hence, all electricity cables, transducer leads and hydraulic pipes are taken out of the rear of the cabinet and connected to their respective sources. A wall mounted control box (plate 7c) is provided so that once the machine has been set up, it can be operated in safety from outside the cabinet.

With the apparatus designed and constructed it was next necessary to develop suitable operating procedures to facilitate the compaction



Wheel - Tracking Test

a : Temperature Cabinet

b : Powerpack

c : Control Box and Recorder

PLATE 7

and testing of specimens. As with the Marshall test, an investigation based upon "trial and error" was undertaken to achieve this end.

5.5.3 Preparation of Constituent Materials:

Constituents were prepared in the same manner, and heated to the same temperatures prior to mixing, as described for the Marshall test, with a couple of exceptions. Due to the larger specimen size, 10 kg compared with 1.2 kg (approx.), it was found necessary to place the batched aggregates on shallow trays rather than in tins and for the reason given in the next section, 2 trays, each containing identical proportions of each aggregate, were required for each specimen. In addition it was also necessary to use the larger sized tins to contain the increased quantities of binder required.

N.B. It was considered necessary to conduct trial mixes to determine the total mass of mix required to produce specimens of approximate equal thickness (approx 50 mm). Although not investigated in this study, the author considered that large variations in thickness may affect the results obtained.

5.5.4 Mixing:

In the absence of a suitable mixer capable of combining 10 kg of material, it was decided to mix each specimen in 2 identical halves, each approx. 5 kg in mass. This was done using a 15 litre capacity, ½ horsepower, Hobart food mixer (Model No. AE125).

Binder was added to the aggregate in the same way as described for the Marshall test, although it was necessary to use a balance of 15 kg capacity.

The aggregates and binder were mixed using the intermediate of the 3 speeds, for 1 minute. The increased quantity of material in the bowl meant that when a modified whisk, similar to that described previously was used, the wire strands were more liable to break. For this reason a more rigid "dough-hook" attachment was modified by the addition of 2 strands of wire and this was found to be satisfactory.

Upon completing the mixing of the first half (5 kg) of a specimen, the mixed material was placed on a tray and returned to the aggregate oven in order to maintain its temperature, whilst the other half was mixed.

5.5.5 Compaction:

This operation was carried out at room temperature using the apparatus set up as shown in plate 5(a), with the roller segment and mould extension in position.

Early work had indicated that in order to achieve the compaction of flat specimens, it was necessary to set the distance of travel of the mould at 305 mm. This was done by altering the position of the "knock-offs" on the table carrying the mould. It was also considered necessary to reduce the speed of travel of the mould from that used during testing, and an arbitrary speed of 25 passes per minute was chosen and set by adjusting control valves on the hydraulic power-pack. In addition it was shown that the compactive effort employed (load on roller segment and number of passes), had a considerable effect upon the degree of compaction achieved, see Chapter 6. It was, therefore, necessary to select a "standard" compactive effort to be used throughout the course of the investigation. For the reasons discussed in Chapter 6, this was to consist of:

> 30 passes of the roller, applying a force of 11.25 N per lineal mm across the width of the specimen, and corresponding to 4 x 72.5 kg (4 x 40 lb) masses on the hanger.

When both halves of a specimen had been mixed they were immediately transferred to the mould, spaded with a spatula to ensure the mixture was seated and even, and then the temperature of the mixture was determined. It was considered impractical to remove the mould from the machine in order to raise it to the temperature required for compaction, but inspite of this, the average temperature of the mixed material immediately prior to compaction was found to be within the range 136 - 144°C. In order to prevent the mixture from sticking to the mould, this had previously been coated with a mixture of limestone dust and water, and, for the same reason, the roller segment was sprayed with water before being brought into contact with the mixture.

The roller segment is lowered by means of the hydraulic ram, until positioned in mould, and the machine set in motion. The number of passes required is pre-set on the control box and the machine counts off the passes and lifts the segment clear of the mould after 30. The compacted specimen is then allowed to cool in the mould for approximately 1½ hours after which time it can be removed. Specimens are then marked with the appropriate specimen identification number and stored in specially constructed wooden boxes (305 x 305 x 70 mm) which prevent deformation of specimens prior to test. Using the procedure outline above, it was found possible to mix and compact 4 specimens during a single working day.

5.5.6 Determination of Specimen Density-Voids:

This was done as described for Marshall specimens except that the weighings in air and water were carried out using a 15 kg capacity balance to an accuracy of 1 gram. It was necessary to modify the balance slightly in order to accommodate a rigid, steel sling arrangement to permit the weighing of the specimens immersed in water.

5.5.7 Wheel-Tracking Test:

Testing was carried out at 45 ± 1°C using the apparatus set up as shown in plate 5(b), with the mould extension and hanger removed, and the segment replaced by the wheel/transducer arrangement. In order to produce the required contact pressure between the wheel and the specimen, a 12 kg steel block was located by means of 2 bolts at the far end of the loading beam. The correct location had previously been determined and marked by adjusting the position of the block whilst allowing the wheel to bear on a load cell, until the required force (525 N) was being applied. Having determined the average contact area of the tyre under this loading by means of a tyre print, it was possible to calculate the contact pressure:

Force on wheel = 525 N
Contact area = 990 mm^2 (approx.)
Contact pressure = 530 kN/m^2 (approx.)
(T.R.R.L. limits = 520 - 550 kN/m^2).

In addition it was also necessary to adjust the distance and speed of travel of the mould to 250 mm and 42 passes per minute respectively.

This was done in the manner described previously. To simplify the former adjustment, once having determined the 2 distances of travel required, permanent metal stops were provided (plate 5b) to facilitate a quick change from one to the other, as the machine was changed over from compaction to testing and vice-versa.

During and prior to testing the air temperature inside the cabinet was thermostatically controlled and the door was kept shut to prevent heat loss. Specimens were placed in the cabinet overnight prior to testing in order for them to attain test temperature. One was positioned in the mould and the others in the wooden boxes previously referred to, stacked on a metal rack such that they were maintained at the working height of the machine.

Each test was to last 45 minutes, or until the rut depth reached 15 mm, which ever was the shorter. It follows that after 45 minutes at 42 passes per minute, 1890 passes will have been completed, and to ensure this was the case, the automatic-counter was set at 2,000 for each test. If at some point during the test, the rut depth reached 15 mm, 2, pre-set limit switches were operated and the test immediately terminated.

Throughout each test, the rut depth at the centre of the specimen was recorded for each pass of the wheel by means of a displacement transducer(195) mounted on the wheel. To provide a datum against which rut depth was to be measured, a datum bar was provided as shown in plate 5(b). Originally a horizontal bar was used but this proved to be unsatisfactory because it was by no means certain that the readout produced referred to the rut depth at the centre of the specimen, and it was also apparent that surface irregularities could lead to spurious measurements. By replacing this with the double-inclined bar shown (plate 5b), and by taking the apex as the datum from which measurements were made, this ensured that rut depth was measured at the centre of the specimen, and measurement was unaffected by surface irregularities. The output from the transducer was fed to the chart recorder(192) and a Rut depth vs. Time curve produced, a typical example is shown in figure 12. The recording equipment set-up and calibration procedure is given in detail in Appendix B.

From the chart recording produced, the following can be determined, given:

Chart speed = 60 cm/hr (1 cm/min)

Full scale deflection of chart = 25 mm

Wheel-Tracking rate (T.R.), the mean rate of increase of rut depth, determined over the final 15 minutes of the test, from figure 12:

Rut depth after 30 mins = 2.8 mm

Rut depth after 45 mins = 3.4 mm

hence

$$\text{T.R.} = \frac{(3.4 - 2.8)}{15} \times 60 = 2.4 \text{ mm/hr.}$$

and also the rut depth (R.D.) after a given number of passages of the wheel, and at the end of the test.

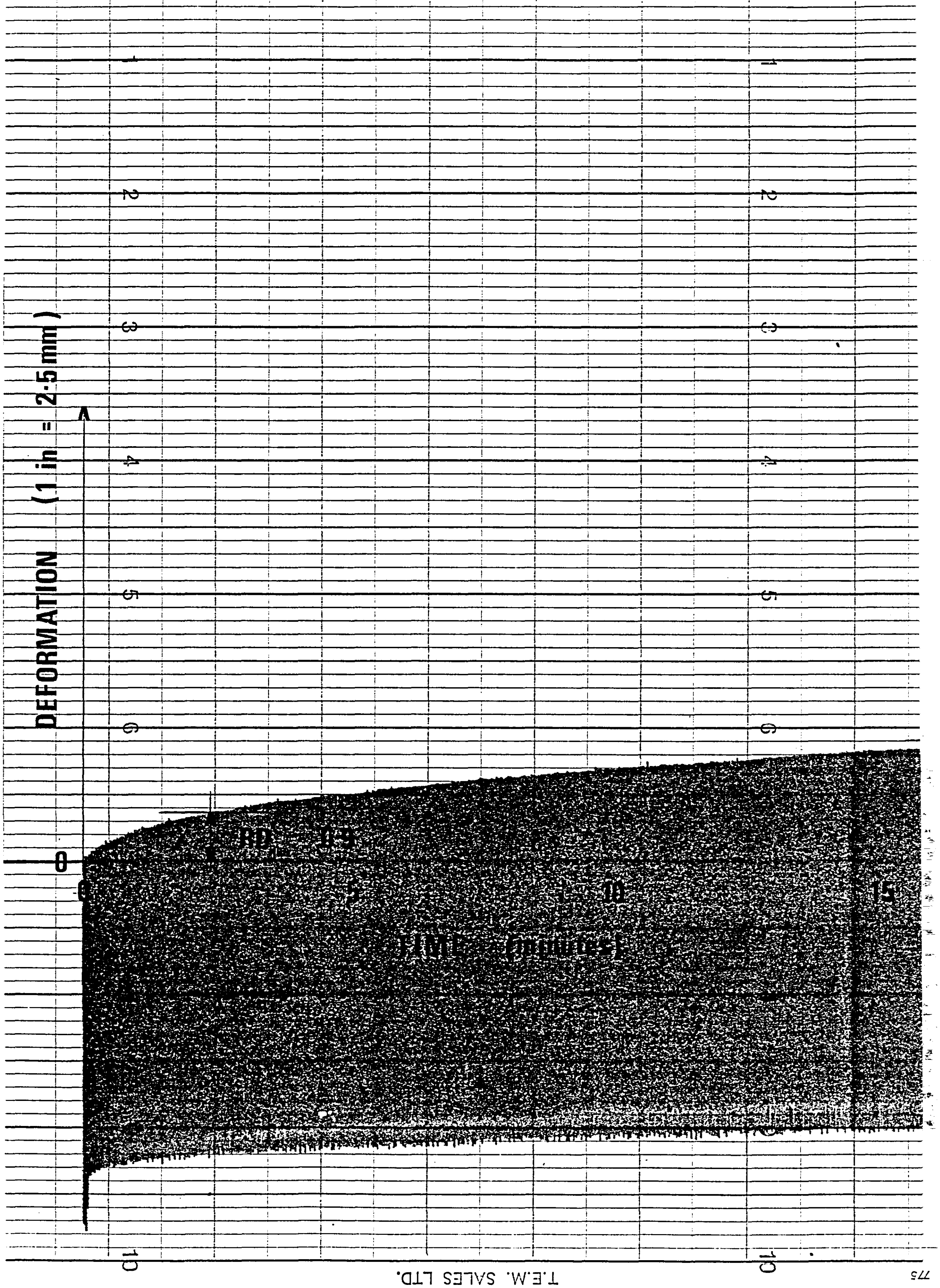
Rut depth after 100 passes (RD_{100}) = 0.9 mm

Rut depth after 1000 passes (RD_{1000}) = 2.6 mm

Rut depth at end of test (RD_{END}) = 3.4 mm.

Upon completion of testing of one specimen, it is immediately

FIG 12


DEFORMATION (1 in = 2·5 mm)
RD = 0·9
0
0
5
10
15
TIME (minutes)
1
2
3
4
5
6
10
T.E.M. SALES LTD.

removed from the machine by dismantling the front and side of the mould, and the next specimen transferred from its box and positioned. Approximately 15 minutes is then allowed for the temperature to stabilise, and after re-checking the recorder-transducer calibration, it is tested in the same manner. Using this procedure it was found possible to test 8 specimens during a single working day.

CHAPTER 6

DISCUSSION OF EXPERIMENTAL RESULTS

6. DISCUSSION OF EXPERIMENTAL RESULTS

6.1 Marshall Test Results

6.1.1 Comments on Test Procedure

6.1.1.1 Introduction

The development of the apparatus and procedures used in the execution of this test has already been described (5.3). In the following sections the author wishes to draw attention to several points arising from this and the subsequent use of the test method.

6.1.1.2 Mixing and Compaction Operations

It was considered essential that the mixing operation should result in the combination of the constituents into a homogeneous mixture, without segregation. In order to determine if this was being achieved the required quantities of each constituent were mixed together as described in 5.3.3 and the resulting mixture then divided into 4 fractions, each representing a layer of material taken in sequence from the mixing bowl. Using dichloromethane as a solvent the binder was "washed" from each fraction and the grading of the remaining aggregate was determined, including any material collected by filtration from the binder-solvent solution. A typical set of results are presented in table 21.

Table 21:

Assessment of Mixing Efficiency:

B.S. Sieve Size	GRADING - Percentage Passing (by mass)				
	Top Layer	Intermediate Layers		Bottom Layer	Desired
5 mm	100	100	100	100	100
2.36	98	98	98	98	98
600 micron	90	90	90	90	90
212	44	43	43	45	46
75	10	10	10	12	13

Taking this a stage further the binder content and aggregate gradation of compacted specimens were determined by the "Extraction Bottle Method : Binder Content by Difference", according to B.S. 598 part 2.(196) Results typical of those obtained are presented in tables 22 and 23.

Table 22

Binder Content Determinations - Marshall Specimens:

Target Binder Content (% by mass)	Binder Content Determined (% by mass) Sample 1*	Sample 2*	Mean of Samples 1 and 2 (% by mass)
9.5	9.58	9.47	9.53
12.0	12.02	12.10	12.06

* Each compacted specimen was divided into 2 samples and the binder content determined for each.

Table 23

Aggregate Gradation - Marshall Specimens:

B.S. Sieve Size	Percentage Passing (by mass)		
	Specimen 1*	Specimen 2*	Desired
2.36 mm	100	100	100
1.18	99	99	99
600 micron	96	97	96
300	71	70	69
212	46	46	44
150	29	29	26
75	17	18	15

* For each compacted specimen the values reported represents the mean of the gradings determined for 2 halves of the specimen.

Taking all of the results into consideration the following has been infered:

(i) the mixing operation used results in a homogeneous mixture of the constituents

(ii) the procedures used in proportioning, mixing and compaction result in the production specimens having within close tolerances, the desired binder content and aggregate gradation,

(iii) neither the mixing nor compaction operations result in any significant aggregate degradation.

The results presented relate to mortar mixtures and it is the author's opinion that the physical nature of such mixtures has a cushioning effect during compaction and hence less aggregate degradation is apparent than reported for Asphaltic Concrete mixtures.(76)(130) It is probable that this will also hold for 30% stone content mixtures but it is likely that for 55% stone content mixtures, degradation may become more apparent although it should be confined to the coarse aggregate.

6.1.1.3 Stability - Flow Determinations

The use of the Load Cell - Chart Recorder set-up described in 5.3.7 is considered by the author to improve upon the method presented in B.S. 594 as it removes the human element from the determinations. There is no problem in obtaining an accurate measure of Stability as the point of maximum force is clearly defined on the chart recording. However, in respect to the determination of Flow several points should be raised.

(i) The determination relies on the fact that load is applied to the specimen at a known, constant-rate of strain throughout the test and that the chart speed is known and also remains constant. In the author's experience the latter does not present a problem and, therefore, any "errors" are likely to result from failure to achieve the former requirement. Provided the deformation rate remains constant throughout the test, any deviation in this from the value specified can be taken account of during the calculation of Flow, and hence the only source of error would be due to variations in deformation rate during the test itself. In the author's opinion such errors would be small although they would increase in magnitude as Flow increased.

(ii) The distance representing Flow on the chart recording (FD) needs to be clearly defined, 3 possible "definitions" of Flow are illustrated in figure 13.

During the present work FD was taken as the horizontal distance from the point where force begins to increase (A), to the point corresponding to its maximum value (B), see figure 13 (a). An alternative to this shown in figure 13 (b) is taken from Dutch specifications(79) and gives a value of FD slightly less than that defined previously. In the author's experience it is sometimes difficult to locate exactly the point at which force begins to increase (A) and it is certainly not always possible to make a determination in the manner of figure 13 (b). For these reasons figure 13 (c) is presented by the author as a further alternative which allows FD to be defined accurately in all instances. This involves constructing a tangent to the curve, passing through the point of maximum force (C) and cutting the zero-line of the chart at D. FD is then taken as the horizontal distance DB.

6.1.1.4 Execution of Test Procedure:

The test procedure was found to depend, for its consistency and reliability, upon speed, organisation and attention to detail. This was particularly true of the mixing and compaction operations to ensure that temperatures were kept within the required limits and to permit the manufacture of 24 specimens in rapid succession. Greater reliability and consistency of operation was achieved when two operatives were used as described in 5.3.8.

6.1.1.5 Reliability of Equipment:

In addition to the above, the reliability of the equipment used was found to be of great importance in achieving consistency of operation. The reliability of testing and recording equipment

Definition of Marshall Flow

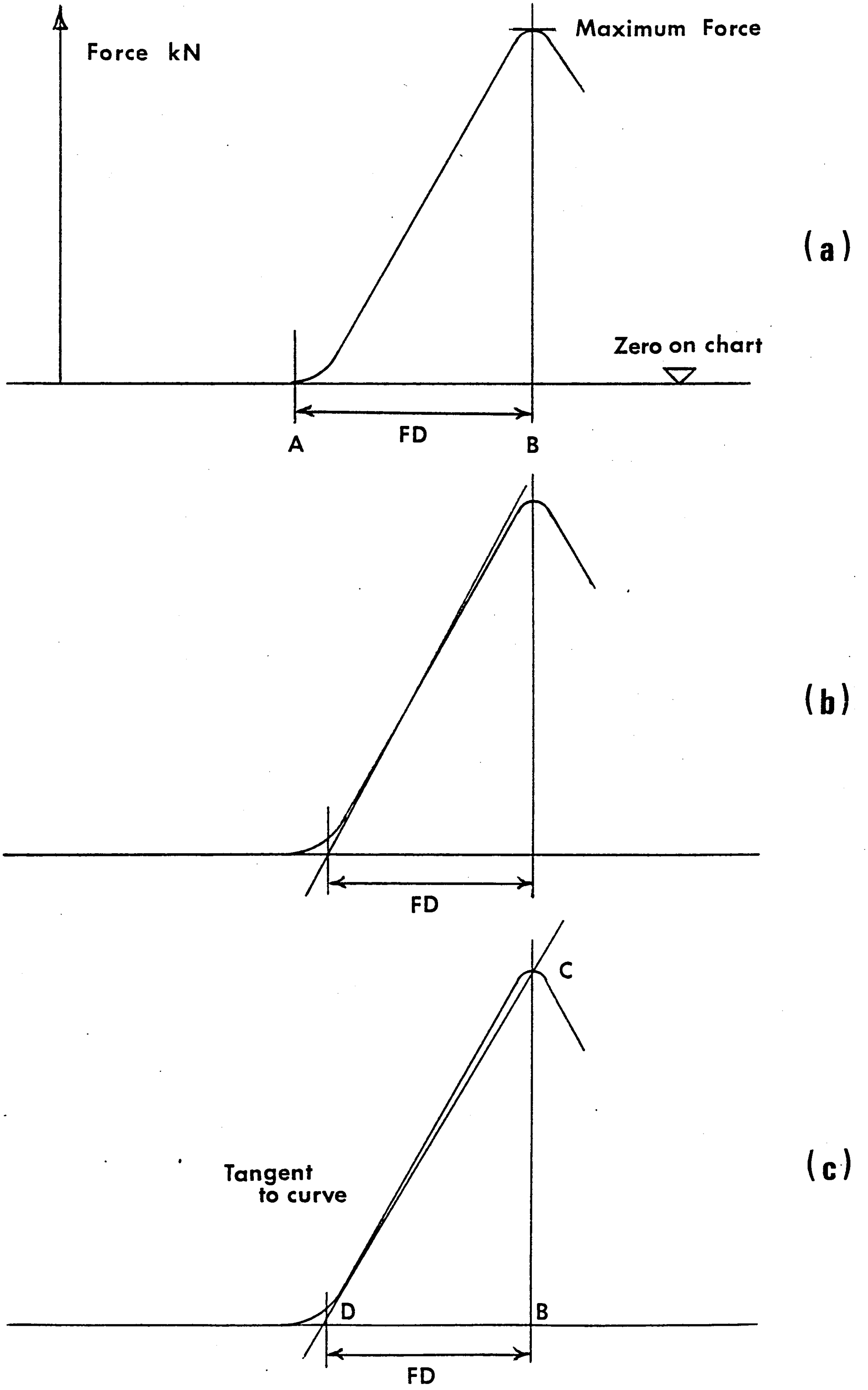


Fig. 13

has already been mentioned but apart from this the compaction equipment was found to be of equal if not greater importance.

It was considered essential to use an automatic compactor to permit the manufacture of 24 specimens within a reasonable time and to remove the inherent variability of the manual method. However, the automatic compactor originally used was found inadequate and suffered from the following deficiencies:

(i) periodic failure to pick-up the hammer resulting in an undetermined number of blows being missed

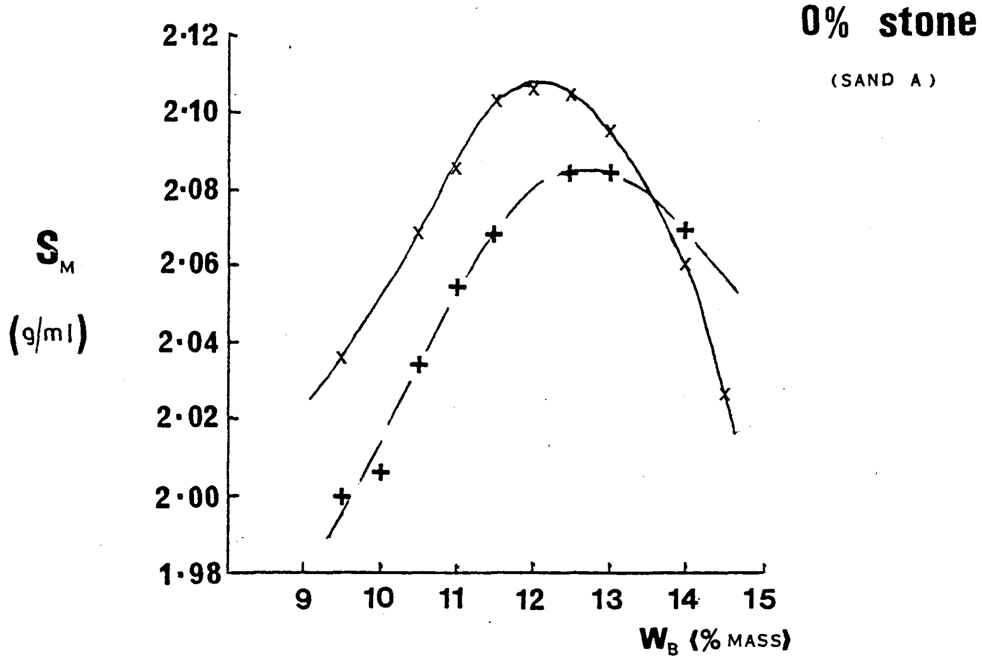
(ii) rebound of the hammer before it was picked up

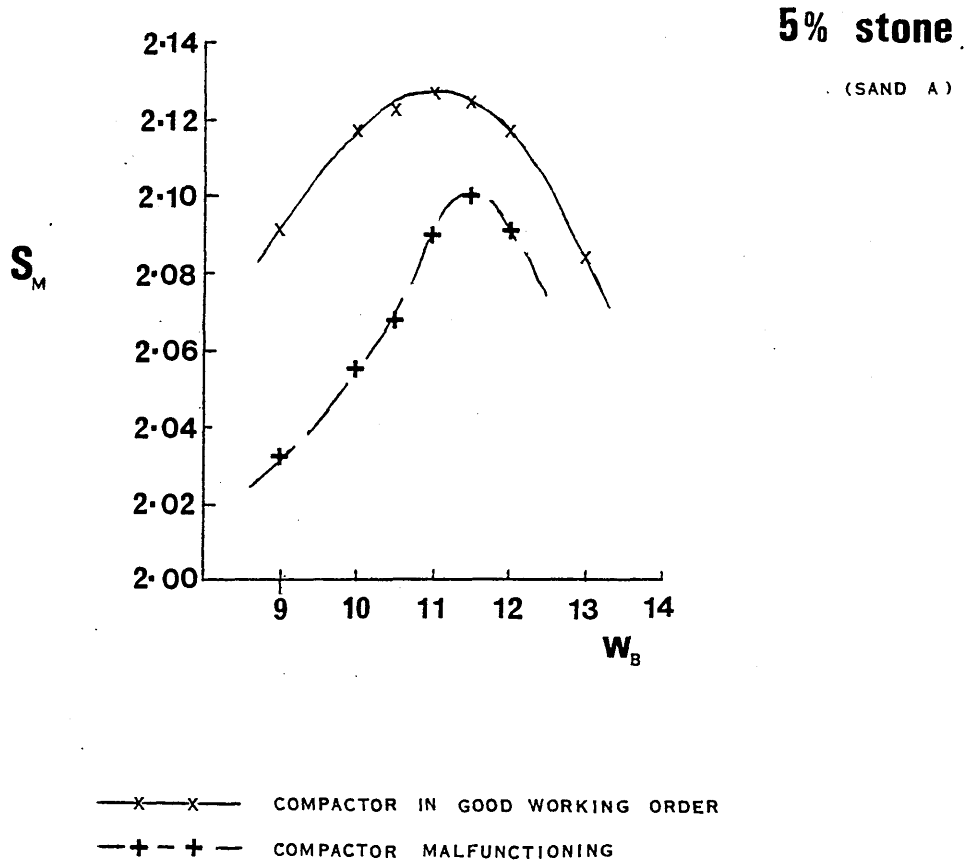
(iii) differential height of drop

(iv) friction between the falling hammer and guide rods resulting in a reduced compactive effort.

A combination of (i), (iii) and (iv) was found to have a significant effect upon the density (S_M) (and hence Stability) of the specimens produced, as illustrated in figure 14, which also indicates an increase in the binder content corresponding to maximum density (S_M) as a result of the reduced compactive effort.

The author considers (i) and (iii) to have resulted from a poorly designed pick-up and release mechanism, made much worse by the fact that the machine was operated at 60 - 70 blows per minute. Further, (iv) was a symptom of the eventual total breakdown of the compactor due to age and the "strain" put on it. A more up-to-date machine, having an improved pick-up and release mechanism was acquired as a replacement. However, this was still found to suffer as a result of the high operating speed and frequently





Marshall Compaction Problems

FIG 14

required adjustment to ensure the hammer was picked up and released each cycle. It is hoped that a new design,(197) introduced recently, will reduce the strain placed upon the mechanism and make for a more reliable machine. It may also go some way in preventing the rebound after each blow is delivered, a problem considered incurable in the earlier designs.

6.1.2 Analysis and Presentation of Results

Marshall tests were conducted using the apparatus and techniques described in 5.3, according to the procedure set out in Appendix B. For each of the Stone Contents considered (table 13), 2 specimens were tested at each of several binder contents, selected to cover the range shown in table 13. Originally 12 binder contents, increasing by 0.5% by mass increments were used according to B.S. 594, but later it was possible to reduce the number of binder contents to 7 or 8 (see later). Where this was done, increments of 0.5% by mass were still used but with a 1% by mass increment included at either end of the range. Additional mixture compositions, not shown in table 13, were used from time to time and these are referred to where applicable.

For each specimen tested the following properties were determined in the manner indicated in 5.3.5, 5.3.6 and 5.3.7.

Relative Density of specimen (S_M)	g/ml *
Compacted Aggregate Density (S_A)	g/ml *
Air Voids in Mix (V_M)	%
Voids in Mineral Aggregate (V_A)	%
Voids Filled with Binder (V_F)	%
Marshall Stability (S)	kN
Marshall Flow (F)	mm
Marshall Quotient (Q)	kN/mm

For each Stone Content, the mean values obtained at each binder content for duplicate specimens are presented in section D.1.3 (sand A) and section D.1.7 (sand B) of Appendix D.

---

* Equivalent to g cm^{-3} but used in this form to maintain consistency with B.S. 594.(7)

For all Stone Contents these values (mean for duplicate specimens) were plotted against binder content (w_B). The resulting graphs for selected Stone Contents (0%. 30% and above) are presented in section D.1.4 (sand A) and section D.1.8 (sand B) of Appendix D. The Low-Stone Content mixtures between 0 and 30% have been omitted as the High-Stone Content mixtures (30% and above) were considered to be more relevant from the practical usage point of view.

6.1.3 Discussion of Results

6.1.3.1 Main Investigation

This was concerned with various aspects of the current B.S. 594 design procedure for mortar mixtures(7) and its extension to mixtures containing up to 55% stone.

In addition to the compositions shown in table 13, this part of the investigation considered the following additional mixtures, containing

(i) sand A and 5% by mass, stone

(ii) sand B "as received" (plus 2.36 mm material included)

with 0, 10, 20 and 30% by mass of added coarse aggregate.

All were treated in an identical manner to the other mixtures (6.1.2), with the results for (i) included along with the other results for sand A in section D.1.3 and those for sand B "as received" in section D.1.6 of Appendix D.

Table 24:

Sand A - Marshall Optimum Binder Contents
(all figures % by mass)

Stone Content (% by mass)	0*	5	10	20	30*	40	55*
Binder Content for Maximum S_M	12.2	11.1	10.7	9.4	8.1	7.3	6.7
Binder Content for Maximum S_A	11.2	9.8	9.8	8.0	7.4	6.6	6.0
Binder Content for Maximum S	12.0	10.8	10.7	8.7	7.5	6.7	5.9
Marshall OBC	11.8	10.6	10.4	8.7	7.7	6.9	6.2

* mean values for duplicate tests

Table 25:

Sand B - Marshall Optimum Binder Contents
(all figures % by mass)

Stone Content (% by mass)	0*	10	20	30	38	55
Binder Content for Maximum S_M	8.1	7.0	6.5	5.4	5.2	4.8
Binder Content for Maximum S_A	7.1	6.2	6.2	5.1	5.0	3.8
Binder Content for Maximum S	6.8	6.2	5.6	4.5	4.4	4.3
Marshall OBC	7.3	6.5	6.1	5.0	4.9	4.3

* mean values for duplicate tests

Table 26:

Sand B "as received" - Marshall Optimum Binder Contents
(all figures % by mass)

Stone Content* (% by mass)	0	10	20	30
Binder Content for Maximum S_M	7.0	6.5	5.4	5.3
Binder Content for Maximum S_A	6.4	5.7	4.6	4.2
Binder Content for Maximum S	6.0	4.9	4.2	3.8
Marshall OBC	6.5	5.7	4.7	4.4

* % by mass of coarse aggregate, in addition to the plus 2.36 mm material contained in the sand.

From the graphs plotted, the binder contents corresponding to the maximum values of S_M, S_A and S were determined and for each Stone Content the Marshall "optimum binder content" (OBC) was calculated as the mean of these 3 binder contents, to the nearest 0.1% by mass. The results of these determinations are presented in tables 24, 25 and 26, for sand A, sand B and sand B "as received" respectively.

(i) Relationship between the Binder Contents corresponding to Maximum S_M, S_A and S, and Stone Content.

The binder contents corresponding to maximum values of S_M, S_A and S are plotted against Stone Content in Figures 15, 16 and 17 respectively.

The author considers that these graphs can be interpreted in two ways, either

1. A curve-linear relationship exists between the two parameters, or

FIG 15

EFFECT OF STONE CONTENT UPON THE BINDER CONTENT FOR MAXIMUM MIX DENSITY

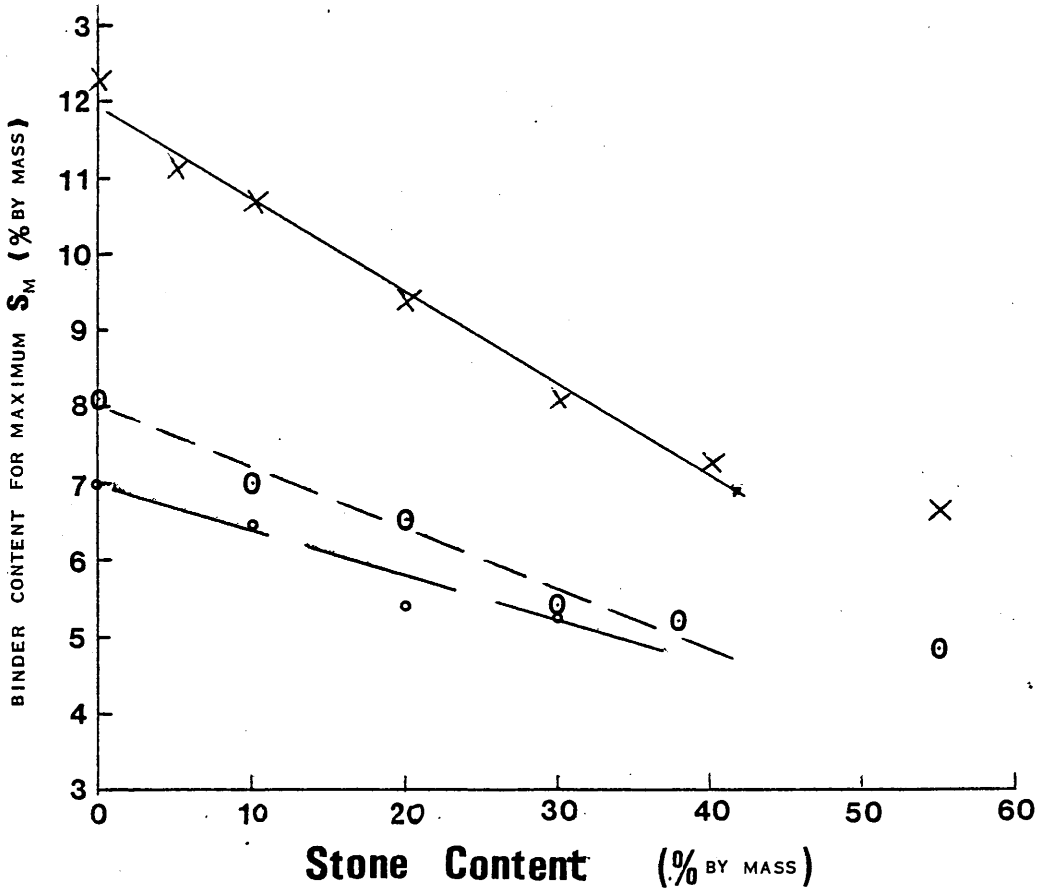
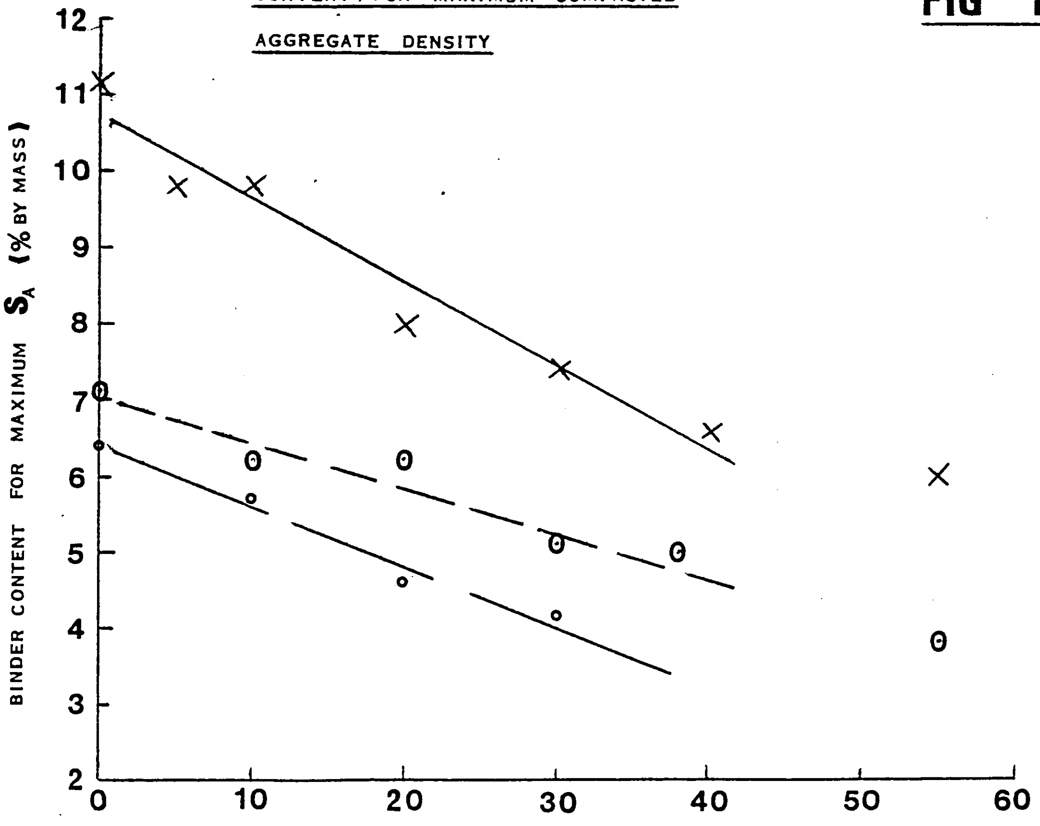


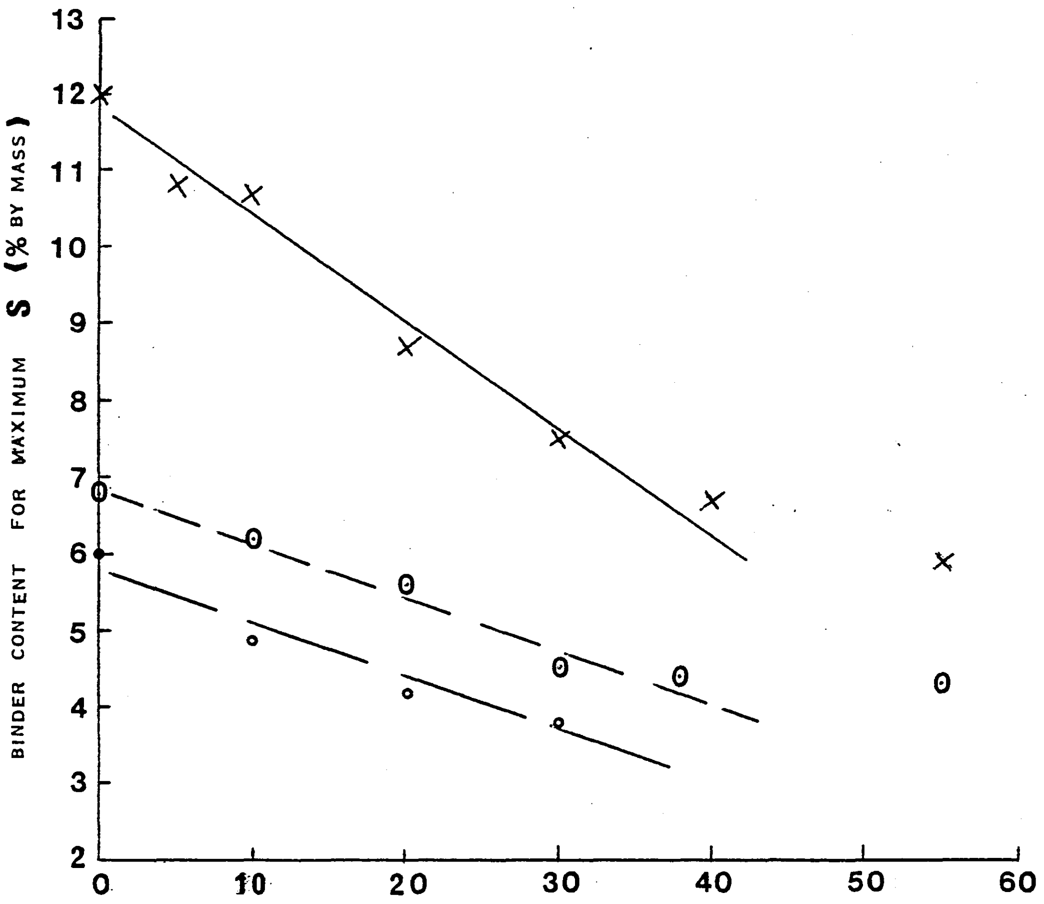
FIG 16

EFFECT OF STONE CONTENT UPON THE BINDER CONTENT FOR MAXIMUM COMPACTED AGGREGATE DENSITY



EFFECT OF STONE CONTENT UPON THE BINDER CONTENT FOR MAXIMUM MARSHALL STABILITY

FIG 17



KEY : (FIGURES 15,16 AND 17)

—×—×— **sand A**

– —o— o— **sand B**

—•— •— **sand B 'as received'**

2. An approximately linear relationship exists, with the binder contents corresponding to the respective maxima being inversely proportional to the stone content. However, the results for mixtures containing 55% stone indicate that this relationship does not hold beyond stone contents of 40% by mass.

The author is of the opinion that the latter is the case, the relationship being of the form:

$$y = c - mx$$

where

y = Binder Content for maxima (% by mass)

x = Stone Content (% by mass)

c = Intercept on y-axis

m = Slope of the straight line.

In each case the Slope (m) of the "best-fit" straight line was determined by Least-Squares Linear Regression (see Appendix E) and the values are presented in table 27. From this it appears that the mean-rate at which binder content for maxima changes with respect to Stone Content decreases as the OBC of the mortar decreases.

Table 27:
Slope (m) of Straight line Relationships indicated in Figures 15, 16 and 17:

SAND	O.B.C. MORTAR	Slope cf Straight-line (m) (for parameter shown vs. Stone Content)		
	(% by mass)	S_M	S_A	S
A	11.8	0.12	0.11	0.14
B	7.3	0.08	0.06	0.07
B "as received"	6.5	0.06	0.07	0.08

(ii) Relationship between Marshall Optimum Binder Content and Stone Content:

For each sand, the OBC's determined as the mean of the binder contents corresponding to maximum S_M, S_A and S are plotted against Stone Content in figures 18 and 19. As would be expected from the preceeding, as Stone Content increases, OBC decreases, and the rate of change of OBC with respect to Stone Content tends to decrease as the OBC of the mortar decreases. At this stage the author was unwilling to infer a linear relationship, as this was not immediately apparent.

Instead, the experimental OBC's were compared with Target Binder Contents based on the B.S. 594 design method. Using the OBC of the mortar, an adjustment is made to yield a Target Binder Content for a mixture containing S% by mass, stone. The tables provided in B.S. 594 to facilitate this are based upon the formula

$$B = A\frac{(100 - S)}{100} + \frac{xS}{100}$$

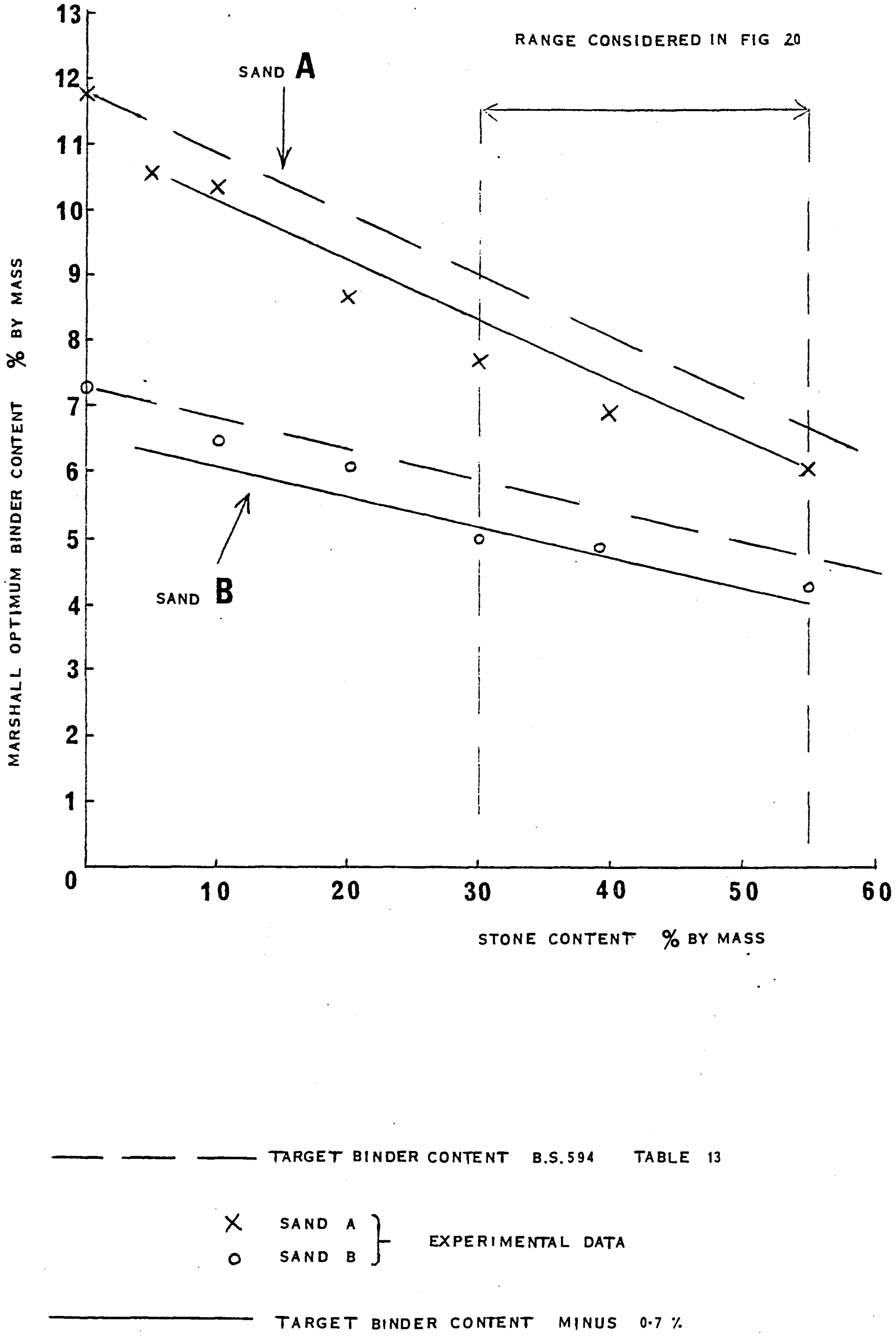
B = Target Binder Content for a mix containing S% coarse aggregate

A = OBC of the mortar (% by mass)

S = Coarse aggregate Content (% by mass)

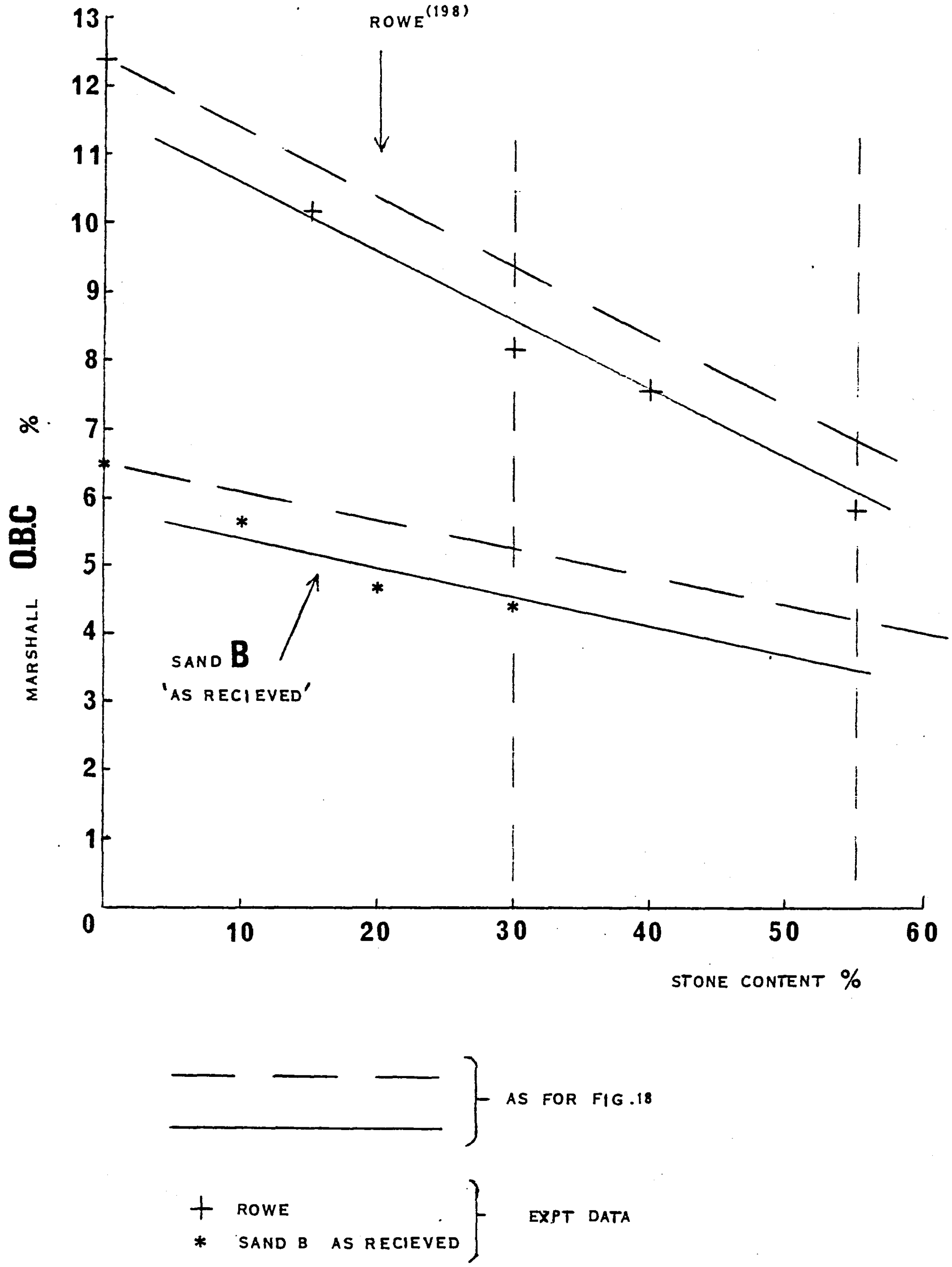
x = 1.3, 2.3 or 2.9 depending upon type of coarse aggregate used.

This allows the mortar portion of mix (100 - S) to have a binder content equal to the OBC (A) determined for it, with an additional x% binder, by mass of coarse aggregate, presumably to coat the stone. For the purposes of this investigation, x took on a value of 2.3 as crushed rock coarse aggregate was used. It can be shown that this figure is derived on the basis of past experience, being equivalent to the amount of binder (% by mass of stone)



Marshall O.B.C vs Stone Content

FIG 18



Marshall O.B.C vs Stone Content

FIG 19

allowed in Schedule 1A recipe mixtures to coat the coarse aggregate.

The Target Binder Contents determined in this manner are included in figures 18 and 19, and define a linear relationship, such that Target Binder Content is inversely proportional to Stone Content. Further, it is apparent that the Marshall OBC's of the Stone-filled mixtures are consistently less than the Target Binder contents for these same mixtures. To look at this more closely, for mixtures containing 30, 40 and 55% by mass stone, figure 20, indicates the relationship between the OBC of the mortar and the OBC of a mix containing 5% stone, for the 3 sands comprising the current investigation, and also including data presented by other workers.(198)(199)(200) For each Stone Content, the relationship appears approximately linear, of the form

$y = mx + c$

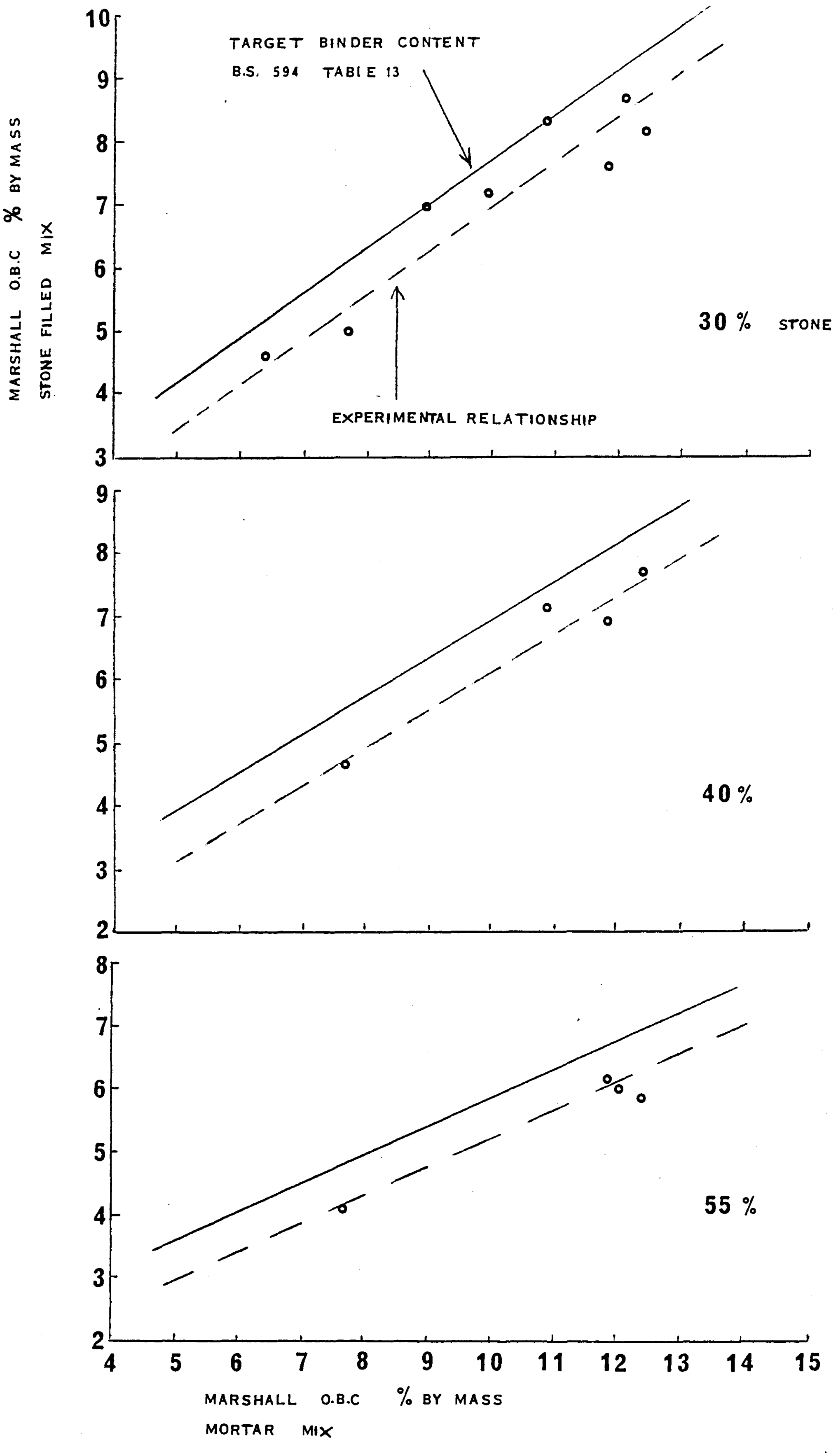
y = Marshall OBC of Stone-Filled Mix

x = Marshall OBC of Mortar

m = Slope

c = Intercept.

The values of m and c were determined by Linear Regression and are presented in table 28 along with the values of m and c for the relationship between OBC mortar and Target Binder Content, based on B.S. 594.



O.B.C Mortar vs O.B.C Stone-Filled Mix

FIG 20

Table 28:

m and c for Straight-Line Relationships indicated in Figure 20.

Stone Content (% by mass)	B.S. 594		EXPERIMENTAL DATA		
	m	c	m	c	r*
30	0.70	0.7	0.67	0.45	0.960
40	0.60	0.9	0.61	0.14	0.962
55	0.45	1.3	0.42	0.92	0.991

* r = Correlation Coefficient (see Appendix E)

There is a high degree of linear association between the OBC of the mortar and the OBC of the Stone-filled mix ($r \geqslant 0.96$) and in addition the slope (m) of the "best fit" straight line through the experimental data is in all cases approximately equal to that of the relationship based on B.S. 594. This being the case, for each Stone Content the value of m was set equal to that corresponding to the relationship based on B.S. 594, and values of c were recalculated assuming that the experimental line passed through the centroidal point of the data. The results obtained are presented in table 29 along with the difference between these values and those for the B.S. 594 relationship.

Table 29:

Re-calculated Intercepts (c) for Relationships in Figure 20.

Stone Content (% by mass)	c on basis of B.S. 594 relationship	c on basis of experimental line with slope = B.S. 594 relationship	Difference
30	0.7	0.0	0.7
40	0.9	0.2	0.7
55	1.3	0.5	0.8

This indicates that if the experimental lines are assumed to be parallel to the B.S. 594 relationship (equal m), then the experimental lines are displaced approximately 0.7% by mass below the B.S. 594 relationship.

In the light of this, the author is inclined to the opinion that in figures 18 and 19, an approximately linear relationship exists between Marshall OBC and Stone Content, certainly over the range 30 to 55% by mass Stone and possibly down to Stone Contents of around 15% by mass. It is further, reasonable to assume that the slope of this relationship is approximately equal to that indicated by the relationship between Target Binder Content and Stone Content, according to B.S. 594, the slope decreasing as the OBC of the mortar decreases. Further, this relationship is displaced approximately 0.7% by mass below the above as indicated in figures 18 and 19. The results of Rowe(198) are presented in figure 19 to further substantiate this argument.

(iii) Effect of using Binder Content for Maximum S_A in the Determination of OBC:

The B.S. 594 (1973) procedure for selection of OBC by means of the Marshall Test, is unique in the respect that the binder content for maximum S_A is one of the criteria upon which the determination is based. Other methods applicable to Asphaltic Concrete(17)(19) rely on the binder contents corresponding to maximum S_M and S, as well as criteria related to void content. The reasons for the introduction of this "parameter" may stem from the following:

(i) The Design Criteria used in connection with Asphaltic Concrete are not applicable in the same form to H.R.A.(56) The requirement may, therefore, be merely a stop-gap measure until void criteria can be defined, in terms of results obtained from Full-Scale Road Trials.

(ii) Optimum binder contents based on maxima for S_M and S alone, may have been considered unsatisfactory in some cases.(57)

Whatever the reasons it was considered worthwhile investigating the effect of using the binder content for maximum for S_A in conjunction with those for maximum S_M and S alone, indicated by Please(57) to be satisfactory in some instances.

Results from the present investigation and other workers(67)(198)(199)(200) indicate that for mortar mixtures, maximum S_A occurs, on average, at a binder content 0.7% by mass less than that for maximum S_M. A similar difference, on average, was also found for mixtures containing up to 55% by mass, stone. Obviously, the use of the binder content corresponding to maximum S_A will have the effect of reducing the OBC compared to an OBC based on binder contents corresponding to the maxima of S_M and S alone. However, for both mortar and stone-filled mixtures this difference was found to be only 0.2% by mass, on average, and, therefore, the effect on OBC is not considered significant.

6.1.3.2 Repeatability and Reproducibility:

This part of the investigation aimed to assess the degree to which test results were repeatable within a single laboratory and reproducible between 2 laboratories.

(i) Degree of Scatter of Test Results:

B.S. 594 requires 2 specimens to be tested at each of 12 binder contents. In an attempt to assess the degree of scatter of results, associated with duplicate specimens, results were analysed in the following manner:-

For each pair of specimens, at each binder content and stone content, for both sands A and B, the Range and Standard Deviation (see Appendix E) were determined for the values of S_M, S and F obtained. Range and Standard Deviation were found not to be influenced by binder content for any given Stone Content. This being the case the mean values (over a range of binder content), for each Stone Content are presented in tables 30, 31 and 32, these values have units as for S_M, S and F, i.e. g/ml, Newtons and mm respectively.

In the case of density (S_M) neither Range or Standard Deviation appears to be affected by Stone Content or sand type. For Stability (S) on the other hand, both measures are affected by both Stone Content and sand type. Both tend to increase as the Stone Content and hence the strength of the mix increases, but an even more pronounced difference occurs as a result of the type of sand used. For Flow (F) both Range and Standard Deviation appear unaffected by Stone Content but again the influence of sand type is considerable.

Table 30:

Density (S_M) - Scatter of results for duplicate specimens

Stone Content	Average RANGE of pairs of specimens		Average STANDARD DEVIATION of pairs of specimens	
	Sand A	Sand B	Sand A	Sand B
0	0.008	0.010	0.006	0.007
10	0.012	0.013	0.009	0.009
20	0.005	0.005	0.003	0.004
30	0.009	0.005	0.006	0.004
40	0.004	0.003	0.003	0.003
55	0.010	0.007	0.007	0.005

Table 31:

Stability (S) - Scatter of results for duplicate specimens

Stone Content	Average RANGE of pairs of specimens		Average STANDARD DEVIATION of pairs of specimens	
	Sand A	Sand B	Sand A	Sand B
0	260	238	184	169
10	338	400	239	283
20	773	223	547	158
30	532	381	376	269
40	264	314	187	222
55	1111	465	786	329

Table 32:

Flow (F) - Scatter of results for duplicate specimens

Stone Content	Average RANGE of of 2 specimens		Average STANDARD DEVIATION of pairs specimens	
	Sand A	Sand B	Sand A	Sand B
0	0.7	0.3	0.5	0.2
10	0.8	0.3	0.6	0.2
20	0.4	0.2	0.3	0.1
30	0.6	0.4	0.5	0.3
40	0.5	0.2	0.4	0.2
55	0.4	0.5	0.3	0.4

The data is further summarised in table 33, indicating the mean values of Range and Standard Deviation associated with duplicate specimens during the course of this investigation. Also included is a measure of precision that can be expected of the mean of duplicate specimens, the Standard Error of the Mean (see Appendix E).

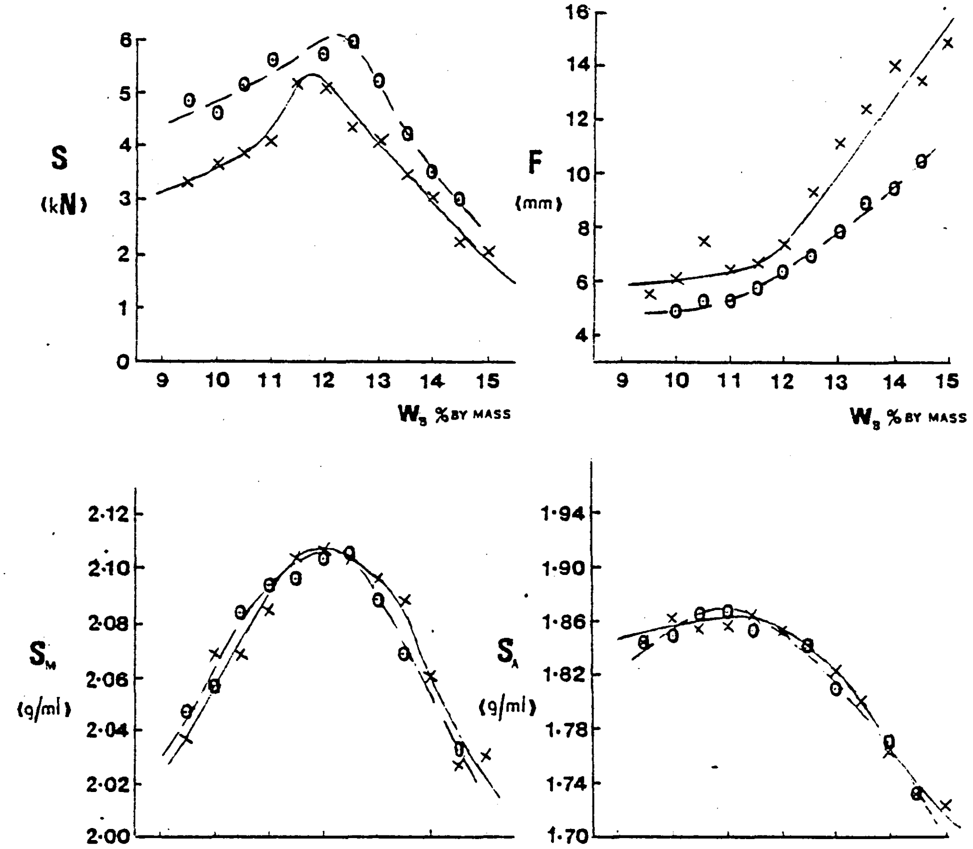
Table 33:

Average Scatter of results for duplicate specimens

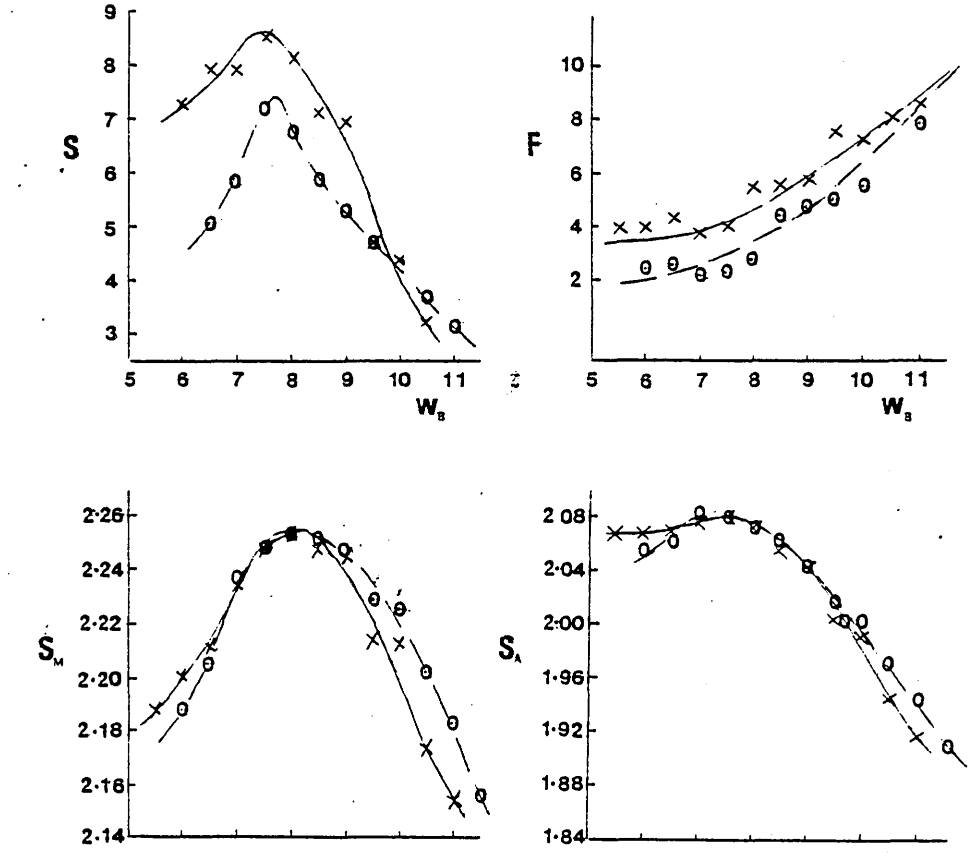
	S_M	S	F
Range	0.008	440	0.5
Standard Deviation	0.006	310	0.3
Standard Error of the Mean	0.004	220	0.2

In view of the fairly high "scatter" of Stability in particular, increased precision (of the mean) may be achieved in any further

0 % STONE



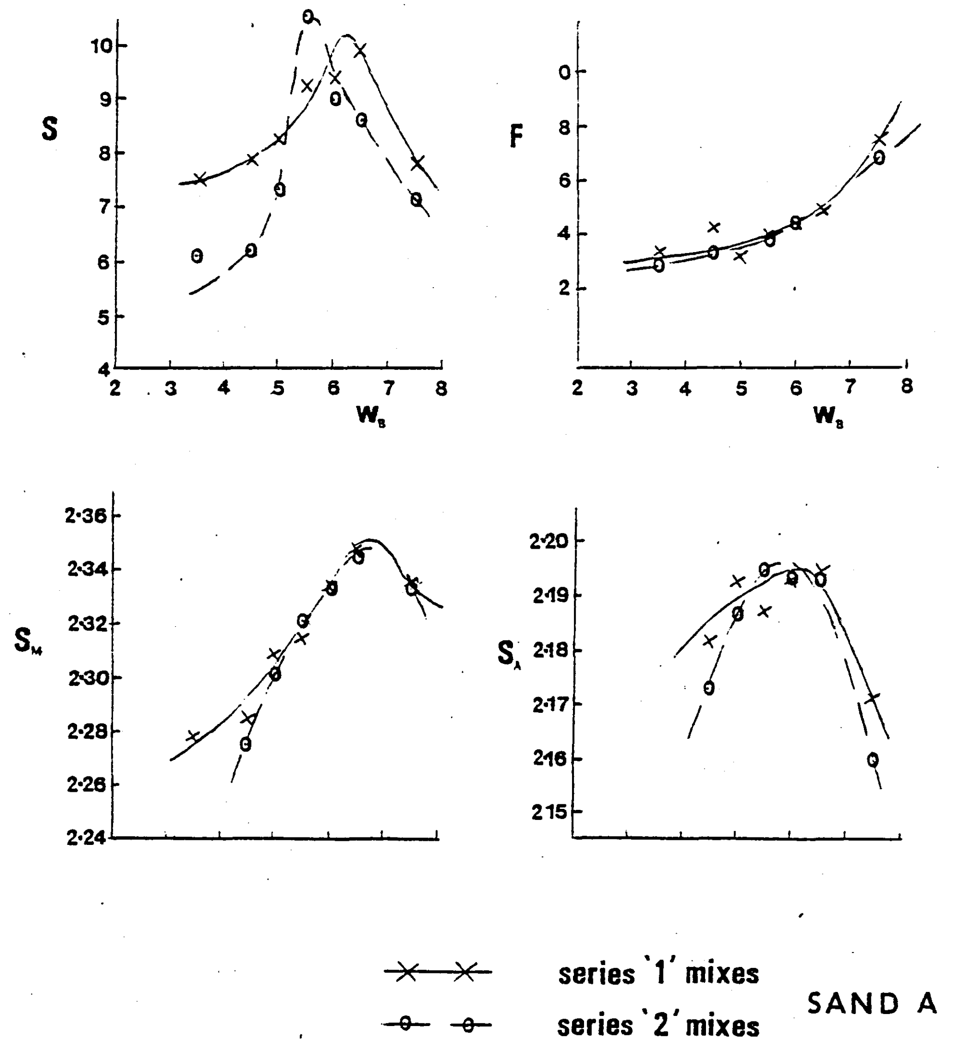
30% STONE



(see over)

FIG 21

55 % STONE



MARSHALL TEST (REPEATABILITY)

FIG 21

work by increasing the number of specimens tested to 4.

(ii) Repeatability:

This was assessed by comparing the results obtained in duplicate tests on mixtures containing sand A, over a range of binder contents, at Stone contents of 0, 30 and 55% by mass. The mean values obtained for duplicate specimens are presented in Appendix D as follows:

First series, tables D.1.3.1, D.1.3.6 and D.1.3.9

Second series, tables D.1.3.2, D.1.3.7 and D.1.3.10.

These results are presented graphically in figure 21. For the 3 Stone Contents considered, the curves of S_M and S_A against binder content (w_B) coincide and, therefore, the mixtures tested in each series maybe considered nominally identical at the time of testing. Results presented later indicate that the average difference between the values of binder content corresponding to maximum S_M and S_A, determined in duplicate tests is only 0.2 and 0.25% by mass, respectively.

In the case of Stability, there is some difference in the values at any given binder content (in particular maximum stability) and also in the binder content corresponding to the maximum value, determined in duplicate tests, see table 34.

Table 34:

Repeatability of Stability and OBC Determinations:

Stone Content (% by mass)	Binder Content for Maximum Stability (% by mass)		Maximum Stability (kN)		Marshall OBC (% by mass)	
	SERIES 1	SERIES 2	SERIES 1	SERIES 2	SERIES 1	SERIES 2
0	11.9	12.3	5.35	5.95	11.7	11.9
30	7.4	7.7	8.60	7.30	7.6	7.7
55	6.2	5.7	10.20	10.60	6.4	6.0

The mean difference in binder content for maximum Stability, between duplicate tests was 0.4% by mass, and the mean difference in the value of maximum Stability, between duplicate tests was approximately 0.75 kN. Further, the mean difference in the OBC determined in duplicate tests was found to be 0.2% by mass.

The author considers the degree of repeatability of the binder contents corresponding to maximum S_M, S_A and S, and the optimum binder content to be acceptable, but the variation associated with maximum Stability values is unacceptable.

(iii) Reproducibility:

A limited amount of co-operative work was conducted at the ESSO Research Centre, Abingdon (E.R.C.A.), to assess the degree of reproducibility of test results.

Initially, mortar specimens containing sand A, at a single binder content were tested at Sheffield and E.R.C.A., the results are presented in tables D.1.3.11 and D.1.5.2 of Appendix D respectively, and are summarised in table 35.

Table 35:

Summarised Results - sand A mortar mix, single binder content (Sheffield - E.R.C.A.)

Laboratory	Number of Specimens (n)	Mean value for n specimens S_M (g/ml)	S (kN)
SHEFFIELD	12	2.098	5.30
E.R.C.A.	6	2.094	5.31

The following statistical significance tests (see Appendix E) were applied to the data in order to determine if the mean values of S_M and S, obtained in the different laboratories were significantly different.

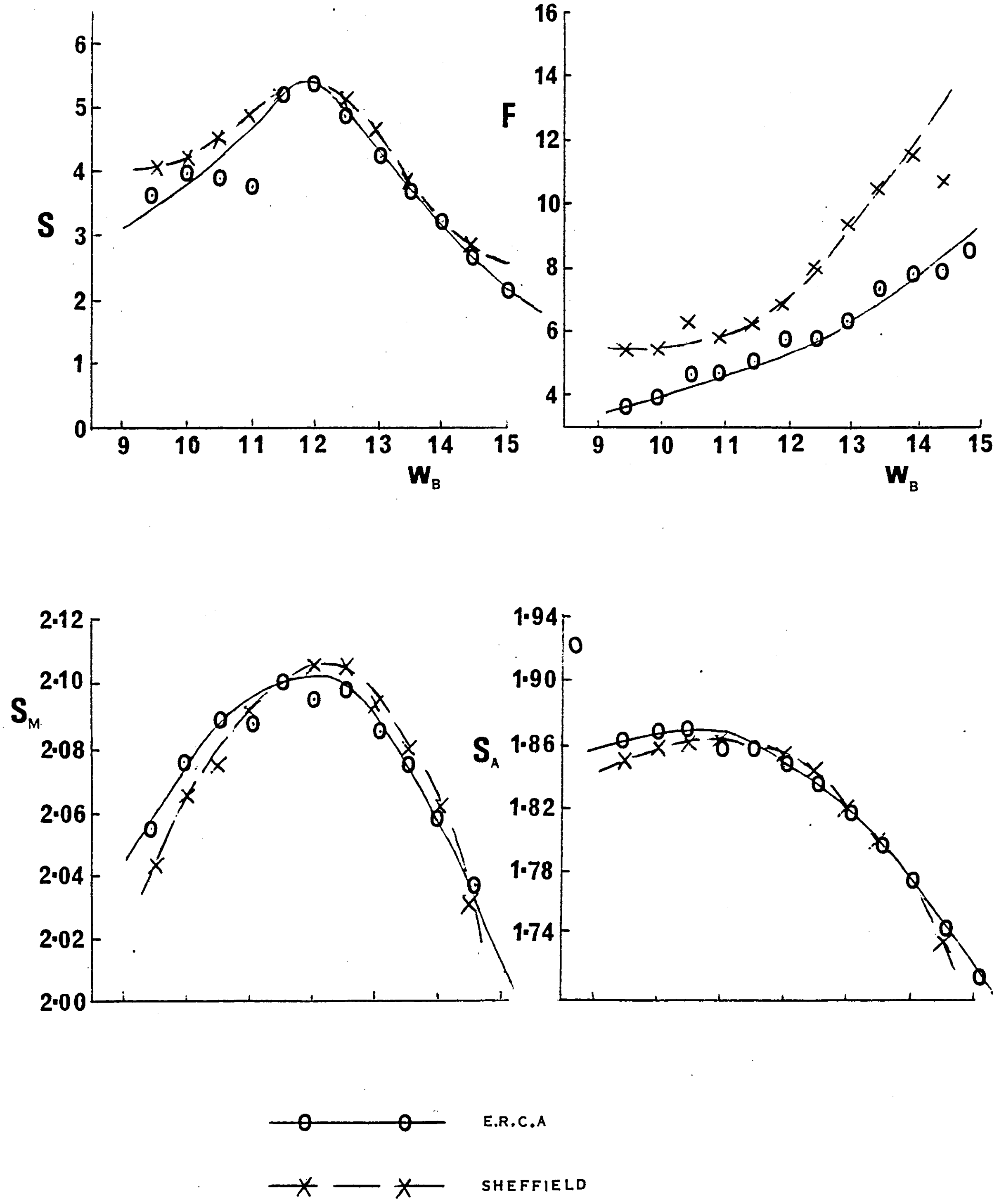
(a) Student's Test (t), applied to samples having homogeneous variances, and

(b) Ratio of Standard Deviations of sample means (tan θ), applied to samples with non-homogeneous variances.

The differences between the mean values of S_M and S were found not to be significant at the 5% level.

A series of duplicate mortar specimens, containing sand A, having the same composition and binder contents as those previously tested in Sheffield (tables D.1.3.1 and D.1.3.2) were then manufactured and tested at E.R.C.A., the results are presented in table D.1.5.1 of Appendix D. These results are presented graphically in figure 22, with the Sheffield results included for comparison.

It can be seen that there is fairly good agreement between the results obtained in the two laboratories. This is substantiated



MARSHALL TEST (REPRODUCIBILITY)

FIG 22

by comparing the binder contents corresponding to the maximum values of S_M, S_A and S, determined in each laboratory. See tables 36 and 37 respectively.

Table 36:
Reproducibility - Binder Contents for maximum S_M, S_A and S, and OBC. (Sheffield - E.R.C.A.)

Laboratory	Binder Content for Maxima (% by mass)			Marshall OBC (% by mass)
	S_M	S_A	S	
SHEFFIELD 1	12.0	11.3	11.7	11.7
2	12.3	11.1	12.3	11.9
E.R.C.A.	12.0	10.9	11.8	11.6

Table 37:
Reproducibility - Maximum values of S_M, S_A and S. (Sheffield - E.R.C.A.)

Laboratory	Maximum Values		
	S_M (g/ml)	S_A (g/ml)	S (kN)
SHEFFIELD 1	2.107	1.864	5.35
2	2.108	1.868	5.95
E.R.C.A.	2.103	1.868	5.50

The results presented indicate a high degree of agreement between the results obtained in the two laboratories. Unfortunately, this has only been determined on the basis of a single set of duplicate results and the author is, therefore, unwilling to take this for granted. However, it would be pleasing to conclude that the effort taken to duplicate both equipment and testing procedure had been rewarded with such a high degree of reproducibility, many more results would be required to substantiate this.

Table 38 includes the results of some other workers using similar materials to those used by the author.

Table 38:

Comparison of Marshall results for sand A mortar mixtures (various sources).

Laboratory	Marshall OBC (% by mass)	Maximum Stability (Newtons)
Sheffield	11.8	5650
E.R.C.A.	11.6	5500
Lab. A (59)	12.5	7010
Lab. B (68)	11.3	7000

Mean	11.8	6290
Range	1.2	1510
Standard Deviation	0.5	830

With these additional results included the degree of variation between laboratories has increased. Further, calculating reproducibility (R), as described by Hills(58)(79) yields:

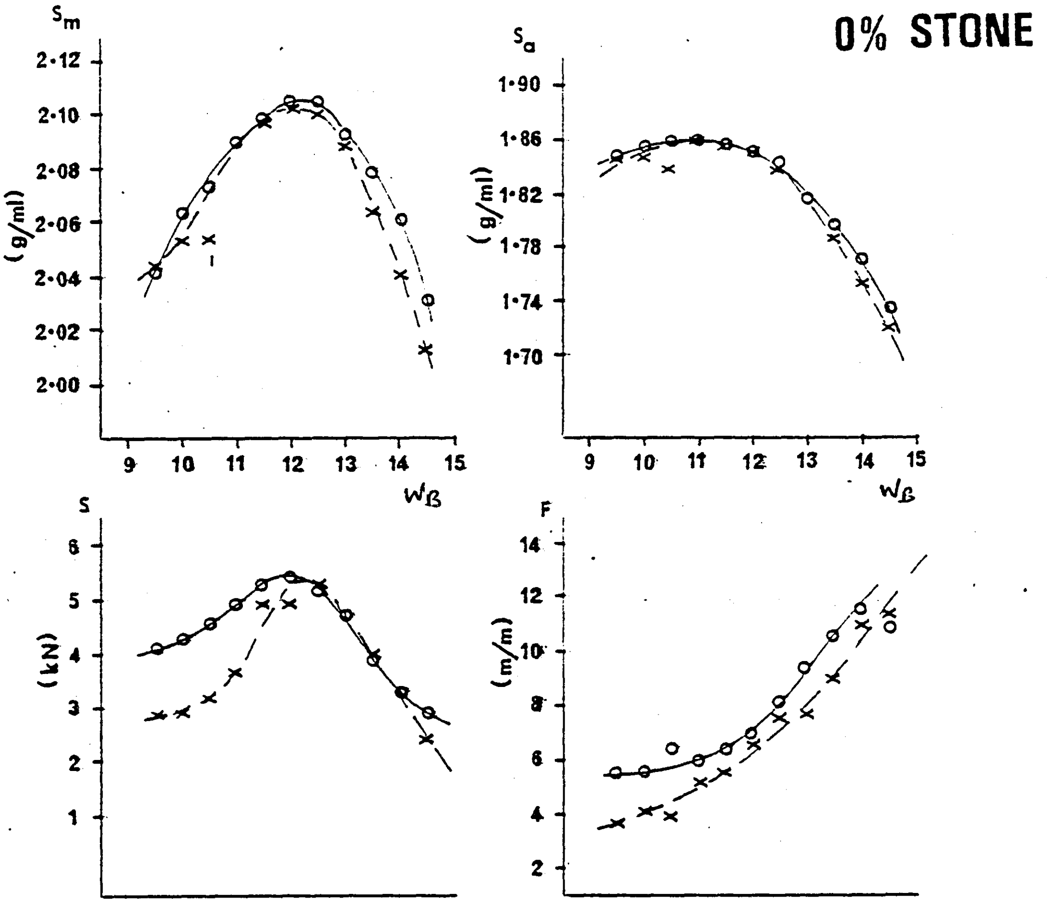
for R = 2.77 x standard deviation and

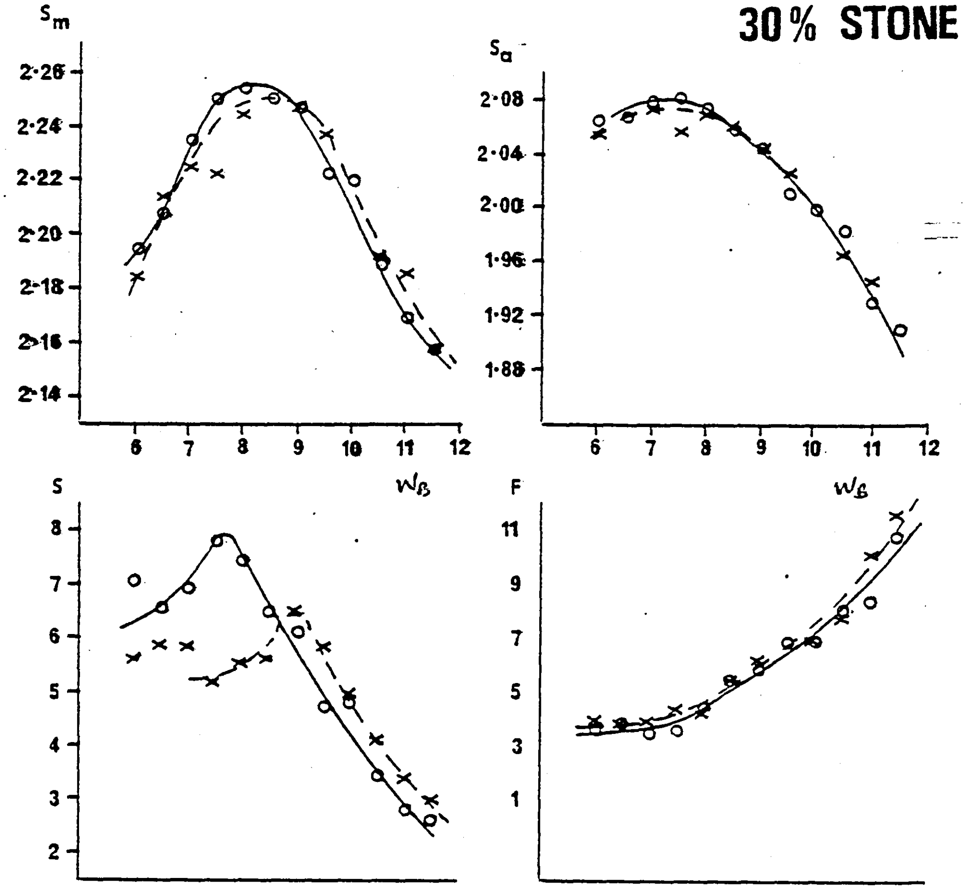
$$R\% = \frac{R}{\text{mean}} \times 100$$

R for maximum Stability = 2.8 kN (37%) and

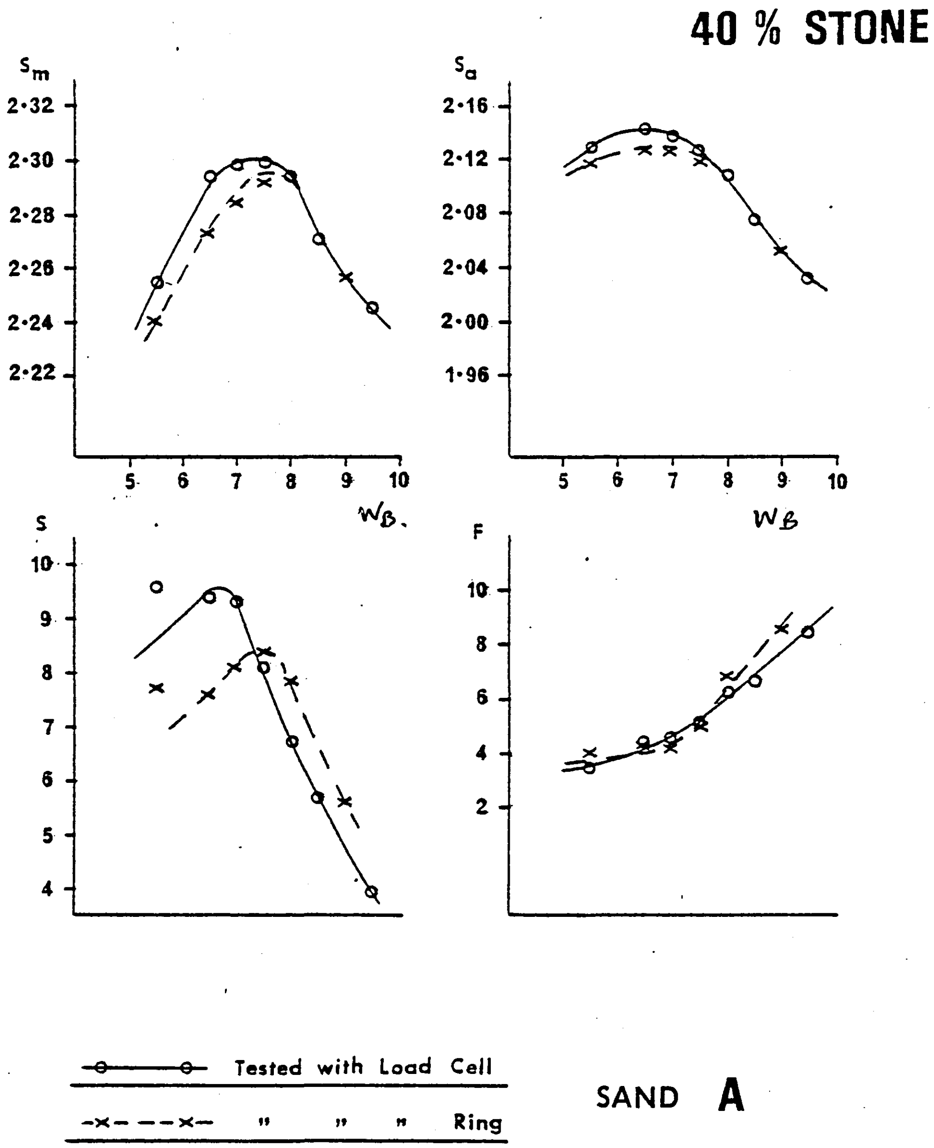
R for OBC = 1.4% (12%).

The above are in good agreement with results obtained in more extensive investigations,(58)(79) presented earlier, and it must, therefore, be concluded that the reproducibility of the Marshall test must be considered to be poor.


0% STONE


30% STONE

(see over) **FIG 23**



MARSHALL TEST (LOAD CELL vs LOAD RING)

FIG 23

6.1.3.3 Method of Measuring Stability:

It has been tentatively proposed that close duplication of testing equipment and operating procedures may result in improved reproducibility of test results. With this in mind and in order to determine if the use of a load cell to measure Stability, in place of a Proving Ring, has any effect on the results obtained, the following work was carried out.

Mixtures comprising, sand A with Stone Contents of 0, 30 and 40% by mass, having the same composition as mixtures for which results have already been presented were tested, with the Load Cell replaced by the Load Ring-Transducer arrangement described in 5.3.7. The mean values obtained for S_M, S_A, S and F, for duplicate specimens are presented in tables D.1.2.1, D.1.2.2 and D.1.2.3 of Appendix D, and are presented graphically, along with results obtained for identical mixtures tested using the Load Cell, in figure 23.

In general, curves for S_M and S_A against binder content are in good agreement and it is, therefore, reasonable to assume that each series of mixes were nominally identical and therefore test method was the only variable. This being so, the following can be noted for all 3 stone contents:

(a) Maximum Stability as measured by the Load Cell is greater than that measured by the Load Ring. The mean difference between Maximum Stability determined by the 2 methods was almost 1 kN. (see table 39).

(b) Binder contents corresponding to Maximum Stability for specimens tested using the Load Cell were less than those determined using the Load Ring. The mean difference in binder content for Maximum Stability determined by the 2 methods was 1.0% by mass. (see table 39).

(c) Flow measurements were unaffected by test method, and in fact the results presented indicate good repeatability.

Table 39:
Effect of Test Method on Marshall Stability.

Stone Content (% by mass)	Binder Content for Maximum Stability (% by mass)		Maximum Stability (kN)	
	CELL	RING	CELL	RING
0	12.0	12.6	5.45	5.35
30	7.5	9.0	7.95	6.40
40	6.7	7.5	9.60	8.40

It can be seen that the differences between test method become more pronounced for the Stone-filled mixtures and that the mean differences are considerably greater than those indicated for duplicate tests when test method was constant. However, when mean difference in OBC, determined by the 2 methods was calculated it was found to be relatively small, 0.3% by mass.

To investigate this further, the following mixtures were tested, 12 specimens of each, by each method

Mortar sand A, single binder content (tables D.1.2.4, D.1.3.11)
30% stone, sand A, single binder content (tables, D.1.2.5, D.1.3.12).

The mean values for 12 specimens tested by each method are summarised in table 40.

Table 40:

Effect of Test Method on Marshall Results (single binder content)

Stone Content (% by mass)	Density (S_M) g/ml		Stability (S) kN	
	CELL	RING	CELL	RING
0	2.098	2.098	5.30	4.80
30	2.247	2.242	6.58	6.15

Statistical significance tests were applied as before and it was found that the difference between the mean values of Stability, determined by the 2 methods was significant at the 5% level. The author, therefore, considers the difference to result from the fact that different methods were used to measure Stability, although more work would be required to prove this conclusively.

The reason for the observed difference is not immediately apparent, although the author considers it may be explained as follows. The Load Ring unlike the Load Cell deforms in order to measure the applied force and this would have the effect of reducing the rate at which load is applied to specimens tested by this method, as compared to those tested by the Load Cell. Coupled with the time-dependant behaviour of bituminous mixtures(173) this would affect the measured strength, (that measured by the Load Cell would be expected to be greater than that measured by the ring). Further, for Stone-filled mixtures, the deformation of the ring would increase (due to increased strength) and, therefore, the disagreement between the 2 methods maybe expected to increase for such mixtures, as indeed was the case.

6.1.3.4 Estimation of Marshall OBC for Mortar Mixtures.

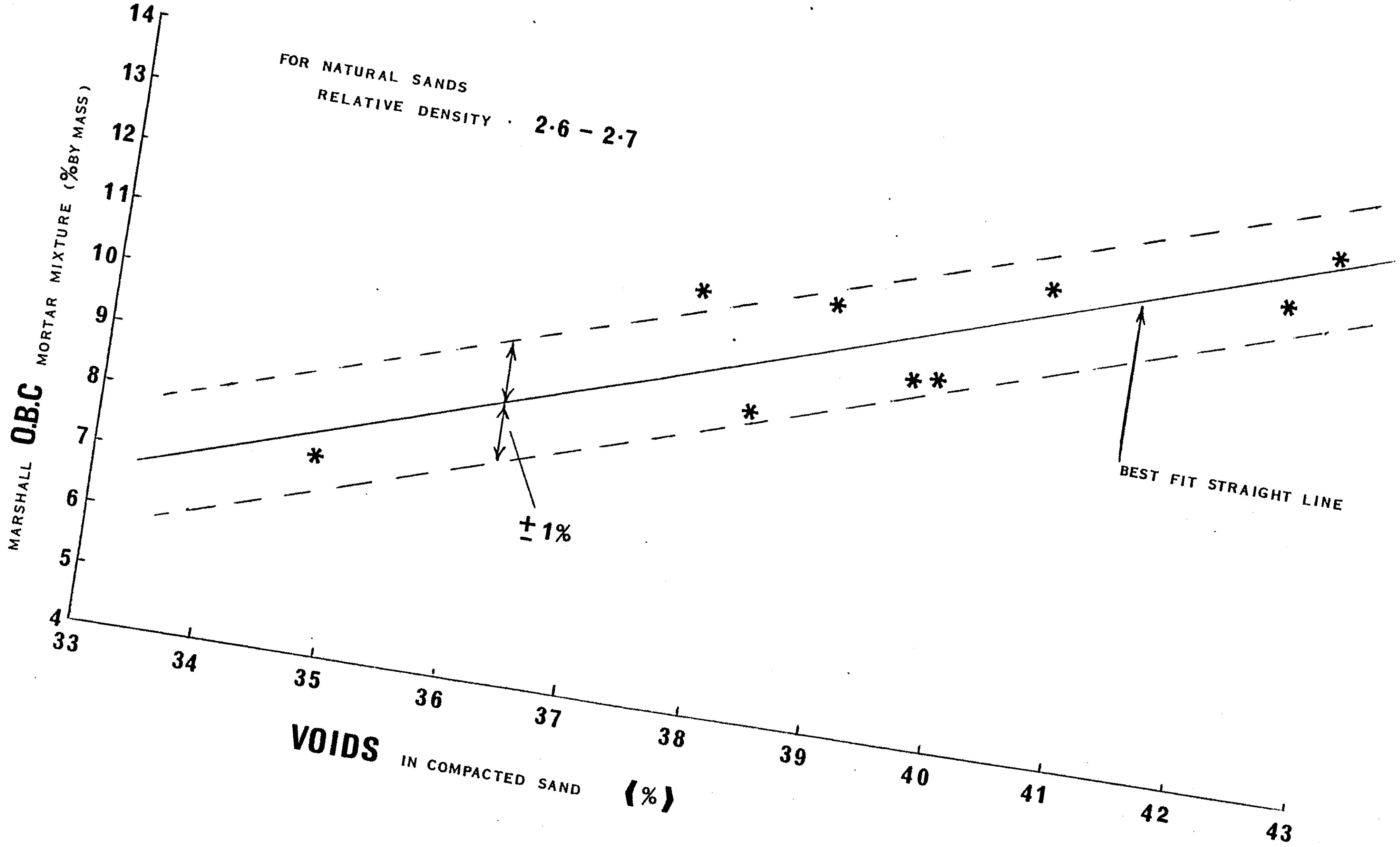
Having conducted several test runs, considerable advantage was derived from the fact that it became possible to accurately predict the OBC of mixtures comprised of similar constituents. This saved the time and effort involved in carrying out preliminary work to establish the range of binder contents over which tests were to be conducted, and also made it possible to reduce the number of binder contents considered in each test.

Similar advantages could be gained if it were possible to estimate the OBC of mortar mixtures prior to carrying out a mix design to B.S. 594. Binder requirement of H.R.A. mixtures is dependant primarily upon the void space present in the compacted aggregate structure, which is controlled to a large extent by the packing characteristics of the sand fraction. For this reason the author decided to investigate the relationship between Marshall OBC and the Void Content of the compacted sand, determined in accordance with B.S. 812, part 2(183) (Compacted Bulk Density Test). The relationship shown in figure 24, is based upon data obtained during the present work but also includes work by Price(67) and Rowe.(198)

A fairly strong linear relationship ($r = 0.9$) exists between, the % Voids in Compacted Sand and the Marshall OBC for mortar mixtures, comprised of that sand. The author considers that a relationship of this type could be used to estimate Marshall OBC to an accuracy of ± 1% by mass, which would be sufficiently accurate for practical purposes. A similar relationship between Marshall OBC and a "modified" bulk density, is reported by Please,(11) but information regarding its use is not widely available.

6.1.3.5 Critique of B.S. 594 Design Method.

It is appreciated that at present, only the mortar portion of



Estimation of Mortar O.B.C

FIG 24

the mix is tested, for the following reasons:

(i) in the normally used, 30% stone H.R.A. mixtures, this portion of the mix is the major constituent

(ii) it is this portion which controls to a large extent, the binder requirement of the mix

(iii) it also plays a large role. [illegible] the strength that will be developed by the mix

(iv) gives slightly better reproducibility.(58)

Although this approach improves upon the recipe method of specification, the application of the design procedure to the Total-mix, coarse-aggregate included, would seem a more logical approach to the problem. In particular, two points related to this arise from the current procedure:

(i) In selecting Target Binder Contents for Stone-Filled mixtures, based on the optimum binder content of the mortar, there is no guarantee that the procedure used leads to the production of mixtures having a composition, and in particular a binder content, most suited to a given application.

(ii) The Design Criteria contained in HD/3/79,(20) in terms of properties of the mortar mix at OBC, in particular those for the highest traffic categories can only be attained by a relatively few available sands.(58)

If the design procedure were conducted on the Total Mix and if Design Criteria were specified in terms of the Total Mix, it is more likely that "optimum" compositions, acceptable from the practical point of view, would be arrived at.

Leaving this aside, in order to bring attention to a few points arising from the execution of the procedure in its present form.

(i) The specification of a constant 6:1 ratio, of sand to filler, unduly limits the composition of the mixtures tested. In particular it takes no account of the effect of % filler and the Filler : Binder ratio, which can have a considerable effect on the properties of sand asphalts.(201)

(ii) The number of binder contents tested (12), is considerable and consequently, mixtures at either end of the range are difficult to manufacture and test, being lacking or too rich in binder.

(iii) Unlike other standards(17)(79) for the Marshall test, the temperatures at which mixing and compaction are to be carried out, are <u>not</u> specified as equi-viscous temperatures. The use of the latter would be of particular importance if binders of different rheological type are to be used.

(iv) Tests are conducted at 60°C which is rather severe in terms of normal U.K. climatic conditions. A temperature of 45°C might be more appropriate for U.K. conditions.

(v) There is no indication given in the standard, as to the degree of precision required of the test results, i.e. repeatability and reproducibility.

The latter, degree of reproducibility is considered to be poor, there are several areas in the present procedure where this may be improved.

(i) Regarding compaction of specimens, the specification of the Automatic compactor alone would be of assistance in removing the inherent variation apparent in the manual method. In addition, some way of assessing the compactive effort, along the lines of the "Penny Test"(153) would be desirable to ensure consistency of results.

(ii) Possible reduction in number of binder contents tested, to allow the number of specimens at each binder content to be increased to 4.

(iii) In view of the results presented in 6.1.3.3, a much more detailed specification of testing method and equipment, would appear to be necessary.

6.1.3.6 Summary of Conclusions

(i) The Marshall test relies for its consistence upon speed, organisation and attention to detail.

(ii) Providing a testing machine capable of applying load to specimens at a constant-rate of strain throughout the test, there is no reason to question the validity of the method described in 5.3.7, for the determination of Stability and Flow. This approach is considered to increase the reliability of these determinations as any human element is removed.

(iii) No practical problems arose from the application of the Marshall test procedure to H.R.A. mixtures containing up to 55% by mass, coarse aggregate.

(iv) Optimum binder contents, determined for Stone-Filled mixtures appeared to be inversely proportional to Stone Content, over the range 30 - 55% by mass.

(v) Target binder contents (for stone filled mixtures) determined according to B.S. 594 appear to be, on average, 0.7% by mass greater than the OBC determined by the Marshall method, over the range 30 - 55% by mass, coarse aggregate.

(vi) For duplicate Marshall test runs in a single laboratory, for H.R.A. mixtures containing between 0 - 55% by mass coarse aggregate, the average difference between runs was found to be:

for, binder content for maximum S_M = 0.2)
binder content for maximum S_A = 0.25) % by mass
binder content for maximum S = 0.4)
Marshall optimum binder content = 0.2)
maximum Stability = 0.75 kN.

(vii) Insufficient data was obtained to allow reasonable assessment of reproducibility. However, it is tentatively suggested that detailed duplication of procedures and equipment may lead to good agreement between results obtained in different laboratories.

(viii) Indications are that values of maximum Stability, and the binder content corresponding to maximum Stability, are influenced by the method employed to measure Stability.

(ix) It is possible to estimate, to an accuracy of ± 1%, the OBC of mortar mixtures, based on the void content of the compacted sand.

6.2 Indirect-Tensile Test Results and Comparison with Marshall Results:

6.2.1 Comments on Test Procedure

6.2.1.1 Introduction

The development of the apparatus and procedures used in the execution of this test have already been described (5.4). What has already been said in sections 6.1.1.2, 6.1.1.3, 6.1.1.4 and 6.1.1.5 regarding Mixing and Compaction, determination of force and deformation, and operating procedures and equipment, for the Marshall test, are also applicable to this method of test as used in the present investigation. In the following sections attention will be drawn to several points, arising from the development and use of this test method, which are applicable only to this method.

6.2.1.2 Validity of Test Method:

It was previously noted in Chapter 2 that a basic requirement of the test is that the specimen fails in tension. Further, if the tensile failure is initiated close to the centre of the specimen there is little reason to doubt the validity of the results obtained.(170) In order to investigate the mode of failure of test specimens, the following mixtures were made up and tested in indirect tension:

sand B, mortar, single binder content (12 specimens)
sand B, 30% stone, single binder content (12 specimens).

The surface of each specimen had previously been coated with a mixture of limestone dust and water, this allowed the point at which a crack first appeared on the <u>surface</u> to be identified and noted. The vertical diameter was divided into 16 zones (see figure 25), and each failure was allocated to one of these zones depending upon where the crack was first noted on the surface. A frequency distribution was built up from the results obtained and is presented in figure 25, both sets of mixtures have been included, as little difference was found between them. It appears that the origin of the failure (appearance at the surface anyway) is in most cases close to the centre of the specimen.

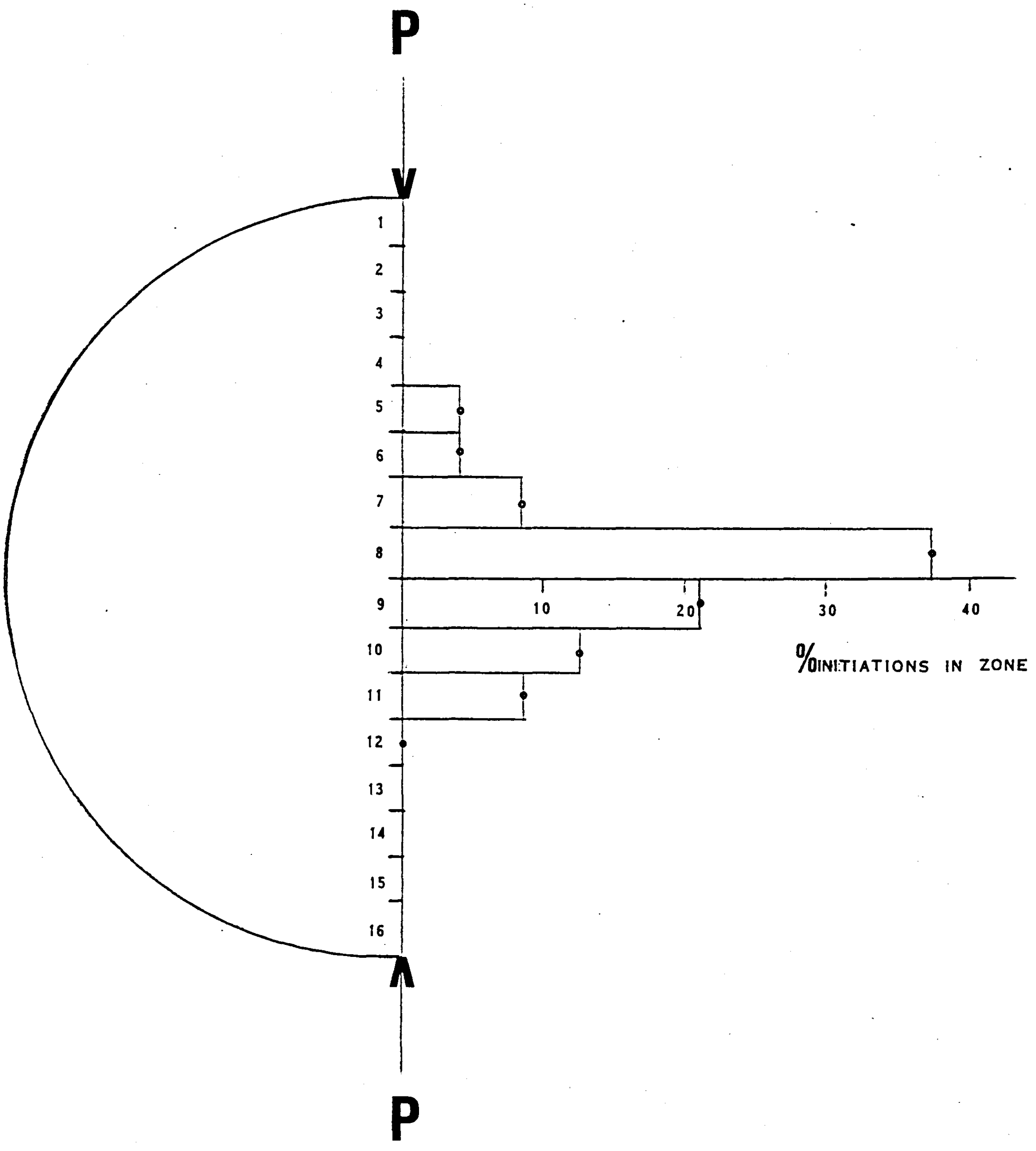
The actual mode of failure of specimens is illustrated in figure 26, which indicates the formation of 'V' shaped wedges at the top and bottom of specimens, with a central vertical plane of failure along the loaded diameter. For specimens containing coarse aggregate, the failure plane was confined mainly to the mortar portion of the mix, although fracture of some coarse aggregate particles was apparent in some cases.

It seemed reasonable to conclude that failure was a result of tensile stress acting perpendicular to the vertical diameter, although the effect of the "wedges" formed during the test, on the measured strength was unknown.

A couple of further points related to testing are worthy of note:

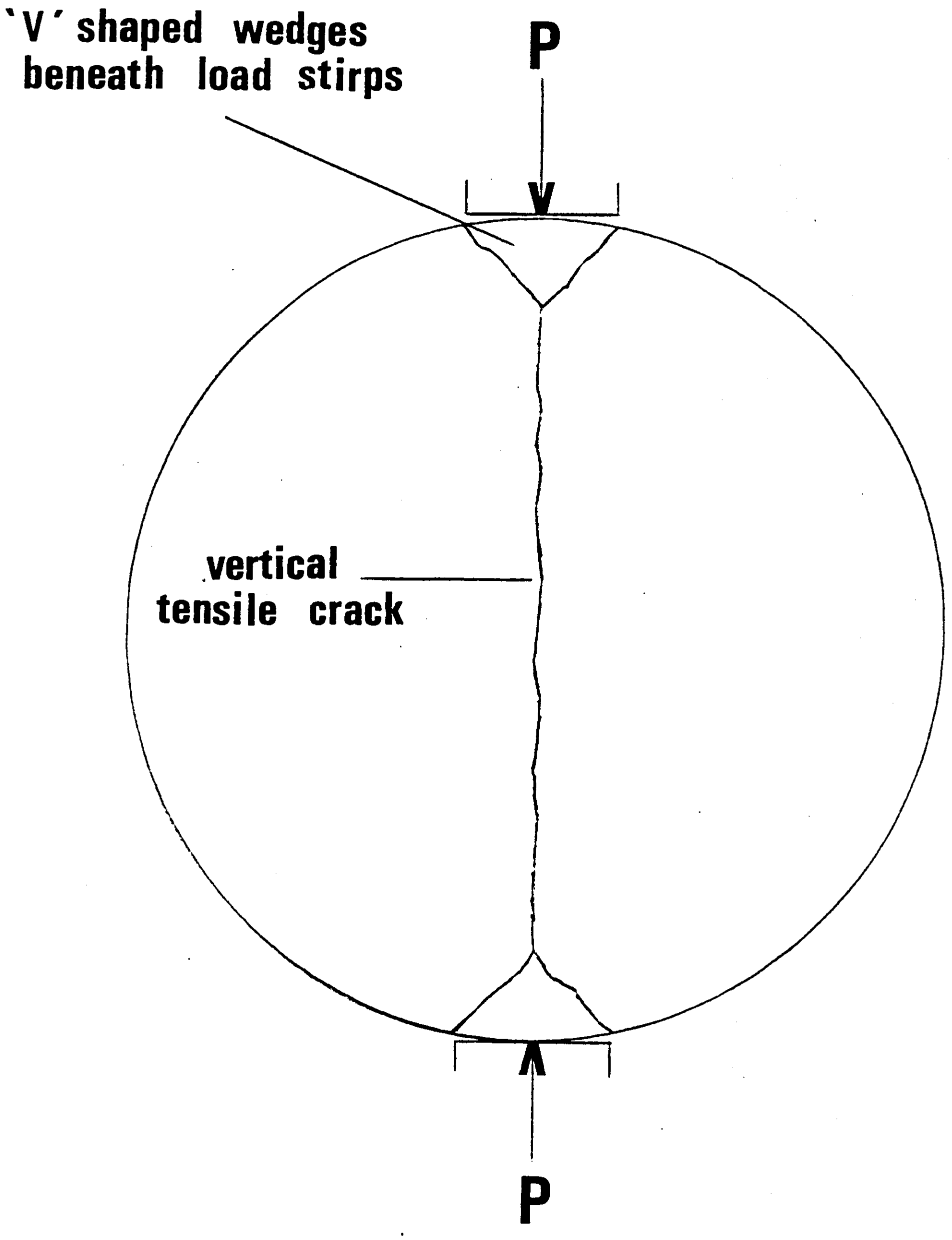
(i) the use of steel loading strips was considered essential as it was considered desirable to measure the vertical deformation undergone by the specimen, at failure

(ii) this method of testing has found extensive application to "brittle" materials, the behaviour of such materials more closely representing that upon which the theory is based. It was hoped that the use of a fairly high rate of strain (50.8 mm/min) during the test, along with the fact that tests were conducted at 25°C



FRACTURE INITIATION - INDIRECT TENSILE TEST

FIG 25



MODE OF FAILURE - INDIRECT TENSILE TEST

FIG 26

would tend to induce the H.R.A. mixtures tested to behave in a manner approximating that of brittle materials. However, this combination may not be condusive to the assessment of factors effecting resistance to deformation.

6.2.1.3 Test Specimens:

Marshall test specimens were found adequate for this purpose for a number of reasons:

(i) the equipment and procedures for their manufacture were already available,

(ii) for the purposes of comparing the results obtained in the Indirect-tensile test with those of Marshall tests on identical mixtures, it was desirable to use the same method of compaction, such that test method was the only variable being considered,

(iii) a limited number of tests at room temperature on specimens 101.6 mm dia x 200 mm long (4 in x 8 in) indicated that the testing machine was not capable of applying sufficient force to cause failure,

(iv) Rowe(198) reports a number of difficulties in fabricating specimens using other methods of compaction, which would have taken considerable time and effort to overcome.

6.2.2 Analysis and Presentation of Results:

Indirect-Tensile Tests were conducted using the apparatus described in 5.4.3, according to the procedure set out in Appendix B.
For each of the Stone Contents considered (table 13), two specimens were tested at each of several binder contents. The binder contents tested, corresponded to those used in the Marshall investigation.

For each specimen tested the following properties were determined in the manner indicated in 5.3.5, 5.3.6 and 5.4.3.

S_M, S_A, V_M, V_A and V_F (see 6.1.2)	
Indirect Tensile Strength (I.T.S.)	N/mm^2
Vertical Deformation at Failure (ΔD)	mm
Tensile Quotient (T)	N/mm

For each Stone Content the mean values obtained at each binder content for duplicate specimens are presented in sections D.2.2 (sand A) and D.2.4 (sand B), of Appendix D.

For all Stone Contents, these values (mean for duplicate specimens) were plotted against binder content (W_B) and smooth curves were drawn through the points. The resulting graphs for selected Stone Contents (0%, 30% and above) are presented in sections D.2.3 (sand A) and D.2.5 (sand B), of Appendix D.

6.2.3 Discussion of Results

6.2.3.1 Optimum Binder Contents Determined from the Indirect-Tensile Test:

This part of the investigation set out to determine if an optimum binder content, for each Stone Content, could be defined in terms of the results obtained in the Indirect Tensile Test, in a manner similar to that used in the Marshall design procedure.

(i) Binder contents for maximum S_M and S_A:

Indirect-tensile test specimens, had nominally the same composition, and were compacted in the same manner as those tested by the Marshall method. Hence it might be expected that the relationship between S_M and S_A, and binder content, would be the same as that found in the Marshall tests, and, therefore, the values of the binder contents corresponding to maximum S_M and S_A could, therefore, be used, in part, in the definition of an OBC. From the graphs of S_M and S_A against binder content, the binder content corresponding to maximum values of S_M and S_A were determined for each stone content and are presented in tables 41 and 42, for sand A and sand B respectively.

Table 41

Sand A - Indirect-Tensile Test Optimum Binder Contents

Stone Content (% by mass)	0	10	20	30	40	55
Binder Content for maximum S_M	12.0	10.8	9.6	8.5	7.7	6.6
Binder Content for maximum S_A	11.0	10.0	8.5	7.2	6.6	5.7
Binder Content for maximum ITS	11.3	10.5	8.8	7.3	6.8	5.2
Tensile OBC	11.4	10.4	9.0	7.7	7.0	5.8

(all % by mass)

Table 42

Sand B - Indirect-Tensile Test Optimum Binder Contents

Stone Content (% by mass)	0	10	20	30	38	55
Binder Content for maximum S_M	8.2	7.2	6.7	5.8	5.5	4.9
Binder Content for maximum S_A	7.1	6.5	6.2	5.7	4.8	4.0
Binder Content for maximum ITS	7.0	6.5	6.0	5.2	4.4	4.2
Tensile OBC	7.4	6.7	6.3	5.6	4.9	4.4

(all % by mass)

If these results are compared with those obtained for the Marshall test (table 24 and 25), in the manner of figure 27, it can be seen that there is good agreement between the two sets of results. The mean difference between duplicate tests being only 0.2 and 0.25% by mass of binder content, for S_M and S_A maxima respectively.

(ii) Binder Content for Maximum Indirect-Tensile Strength

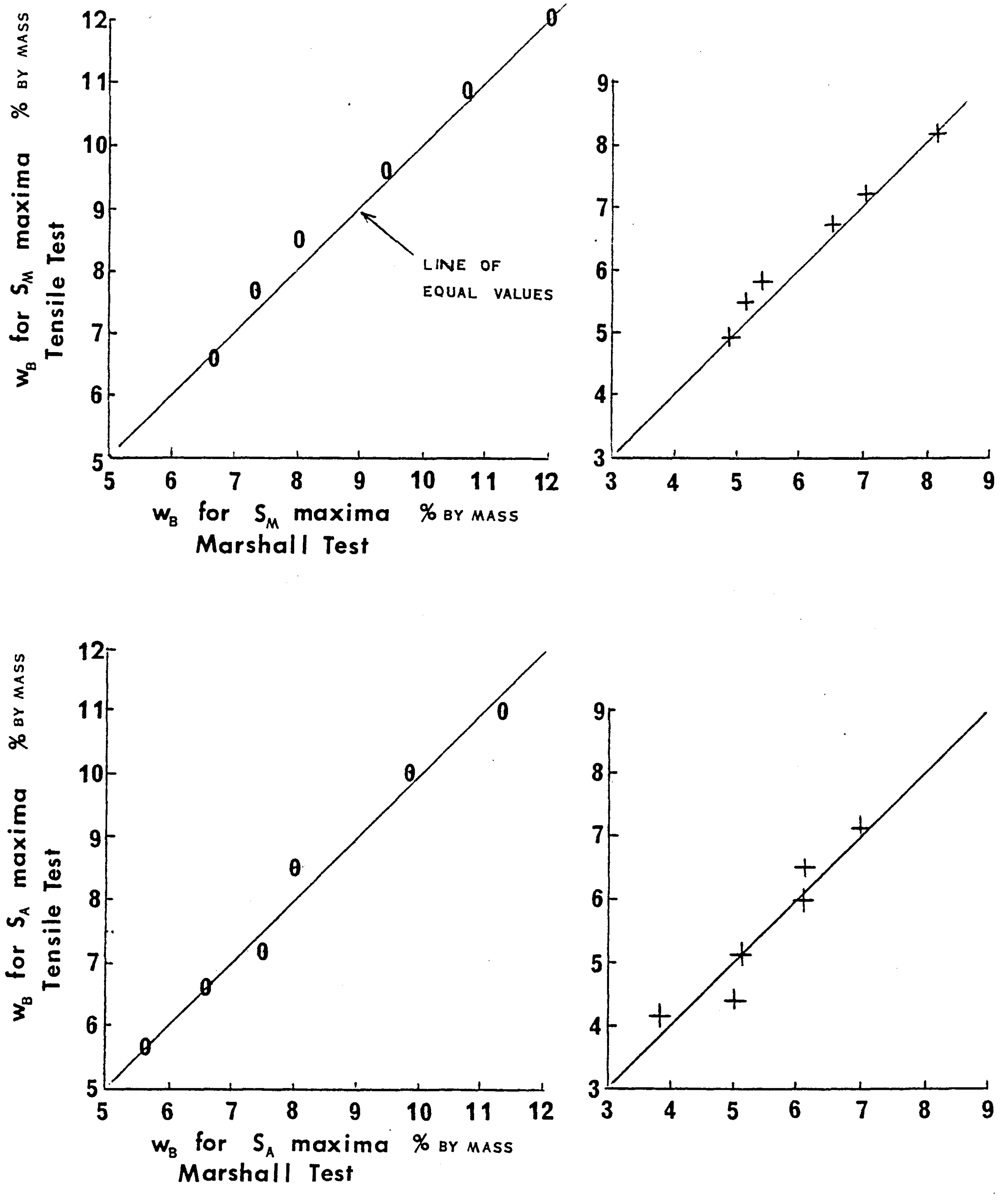
The graphs of ITS against binder content (appendix D) indicate that like Marshall Stability, as binder content is increased, ITS increases to a maximum and then falls off. It is, therefore, possible to use the binder content corresponding to Maximum ITS, in defining an OBC.

For each Stone Content, the binder content corresponding to maximum ITS has been determined and is included in tables 41 and 42 for sand A and sand B respectively. If the binder contents corresponding to maximum ITS are compared with those corresponding to maximum Marshall Stability, for each stone content, as in figure 28, it can be seen that in each case these two binder contents are approximately equal. The mean difference between the two is 0.3% by mass of binder content.

In the author's opinion the fact the specimens for both tests were compacted in the same manner goes a long way to explaining this observation.

(iii) Optimum Binder Content based upon Indirect-Tensile Test Results

It is possible, therefore, that an OBC, defined in terms of Indirect-Tensile test results, (based on the mean of binder contents corresponding to maximum S_M, S_A and ITS) might be in close agreement

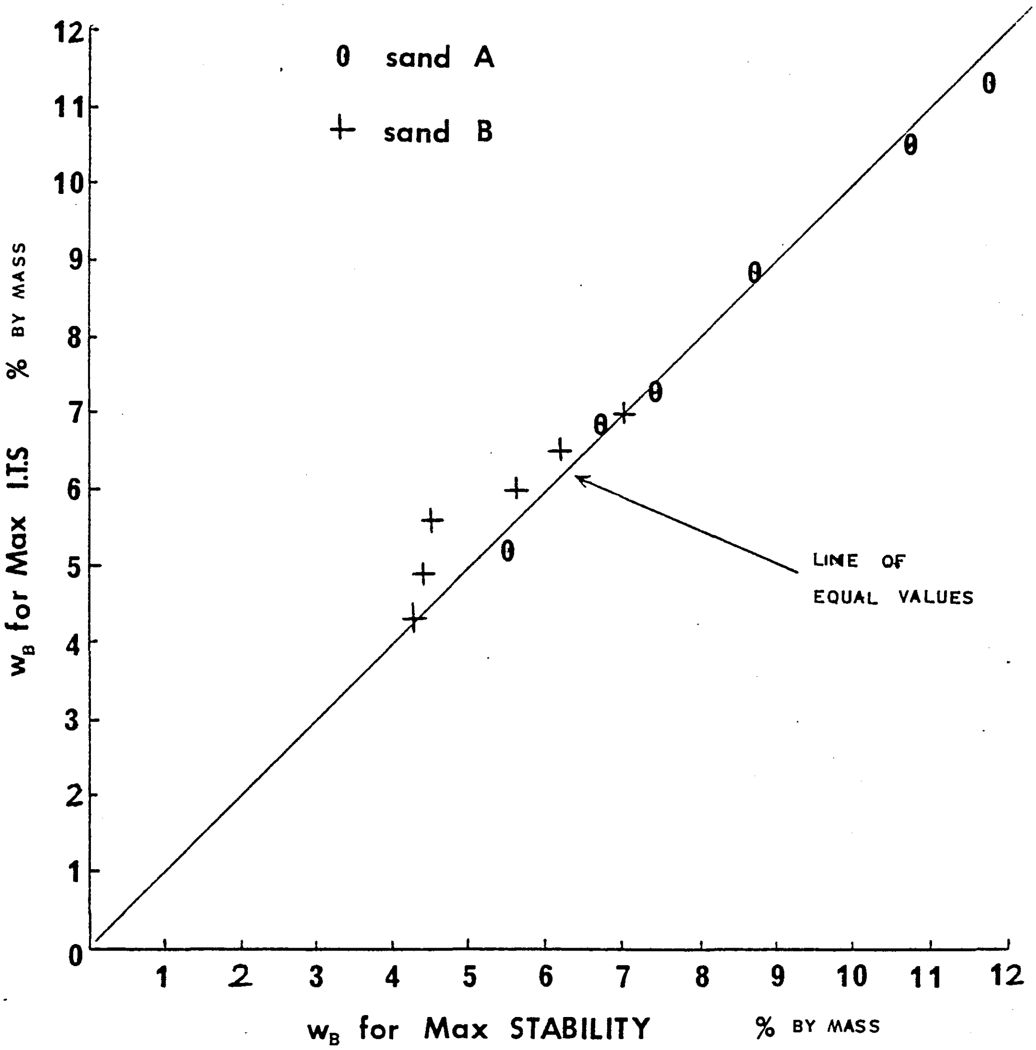


sand A (0)

sand B (+)

Comparison of Binder Contents corresponding to S_M and S_A maxima in Marshall and Tensile Tests

FIG 27



Comparison of Binder Contents
Corresponding to Maximum S and I.T.S

FIG 28

with Marshall OBC's for the same mixtures.

OBC's determined for each Stone Content, in the above manner are included in tables 41 and 42 for sand A and sand B respectively, and are compared with Marshall OBC's for the same mixtures in figure 29. The mean difference between the OBC's determined in each manner, at each Stone Content, and is less than 0.2% by mass of binder content.

The author considers this good agreement to have arisen for the reasons stated previously, and therefore, taking results at face value may not give a clear representation of the actual situation.

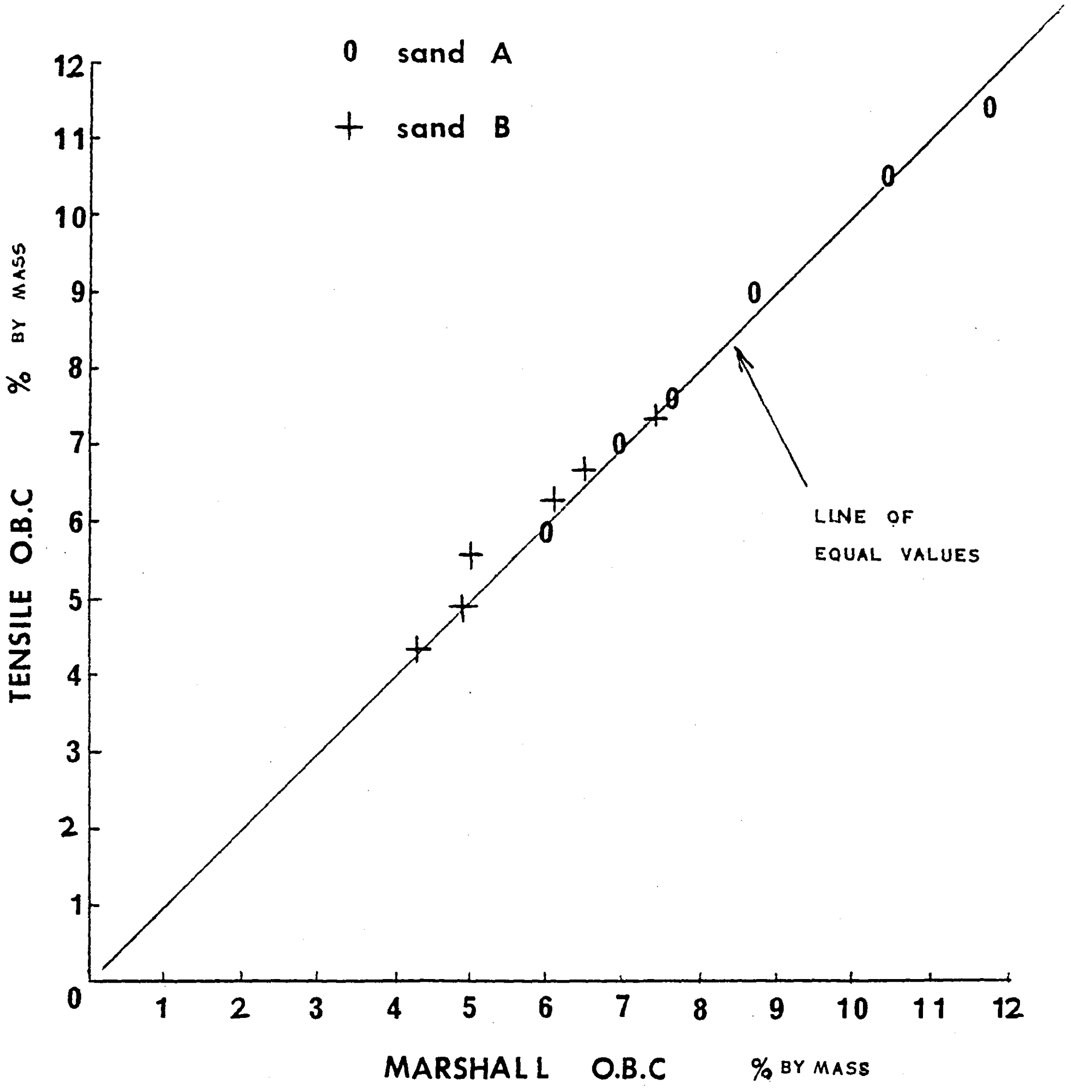
6.2.3.2 Comparison of Marshall and Indirect-Tensile Results:

As mentioned earlier, specimens for both tests had nominally identical composition and were compacted in the same manner. Therefore, when comparing the values of "strength" determined by each method, the only variable should be test method (method of load application, temperature, and parameters measured).

It has been shown that the binder contents corresponding to maximum S_M and S_A, for each series of specimens tested by each method, differed very little. Taking this a stage further, figures 30 and 31, indicate how well the curves for S_M against binder content are in agreement, for each Stone Content, for sand A and sand B respectively.

Taking the results as a whole, there is good agreement between the curves for specimens tested by each method.

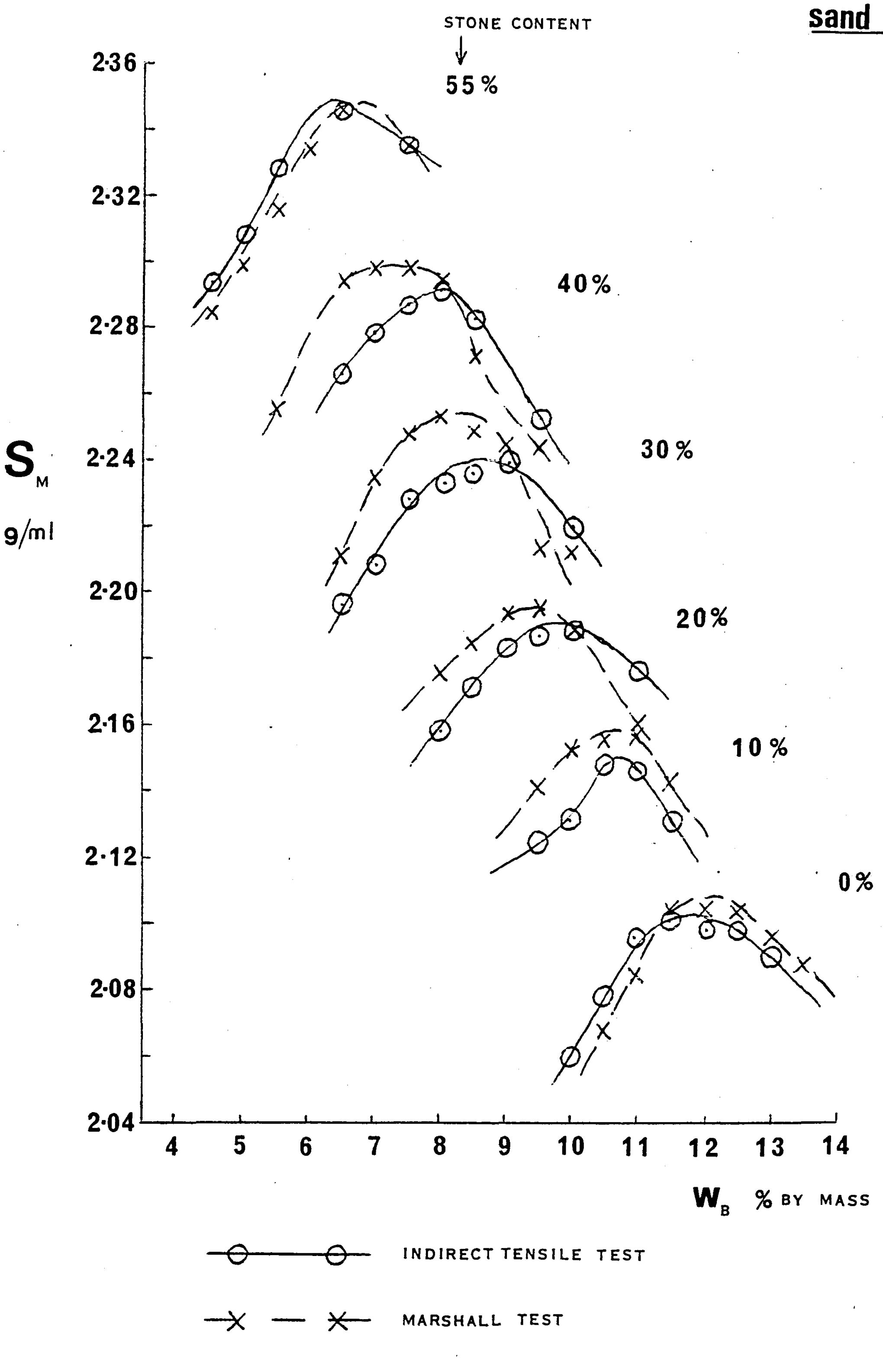
N.B. slight deviations from this for sand A at Stone Contents



MARSHALL O.B.C vs TENSILE O.B.C

FIG 29

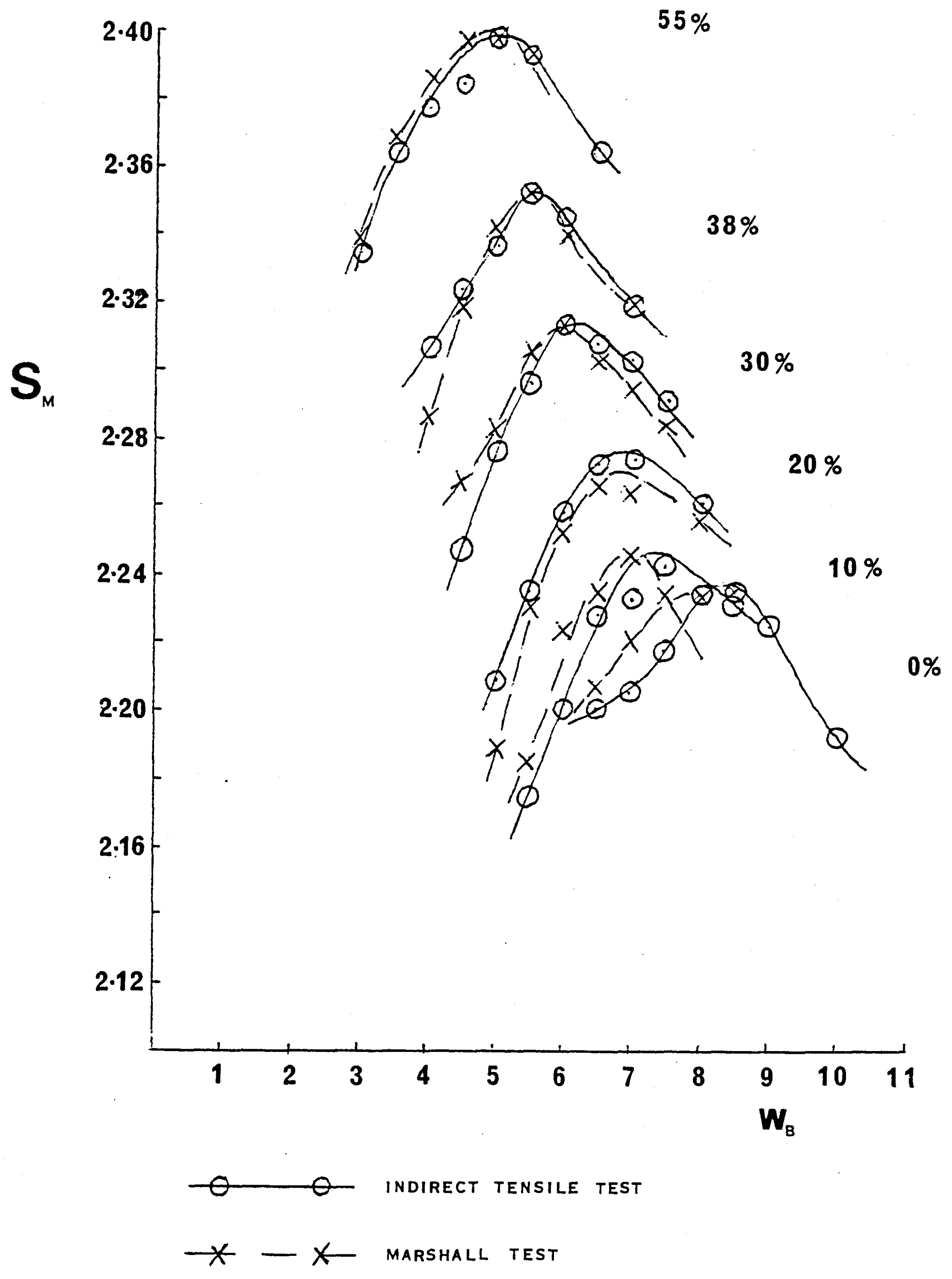
sand A



Specimen Density - Marshall Compaction

FIG 30

sand B



Specimen Density – Marshall Compaction

FIG 31

of 30 and 40% by mass were due to malfunctioning of the compactor, mentioned earlier.

It is, therefore, reasonable to assume that test method is the only variable when comparing results obtained for similar mixtures.

(i) Marshall Stability vs. Indirect-Tensile Strength:

For each sand, at Stone Content, the values of Marshall Stability (S) and Indirect-Tensile Strength (ITS) determined (each for duplicate specimens) at each binder content, were extracted from the appropriate results tables (appendix D) and plotted as shown in figure 32. In each case, an approximately linear relationship exists between S and ITS, of the form

$$y = mx + c$$

y = Indirect-Tensile Strength ($N/mm^2 \times 10^{-1}$)

x = Marshall Stability (kN)

c = Intercept on y-axis

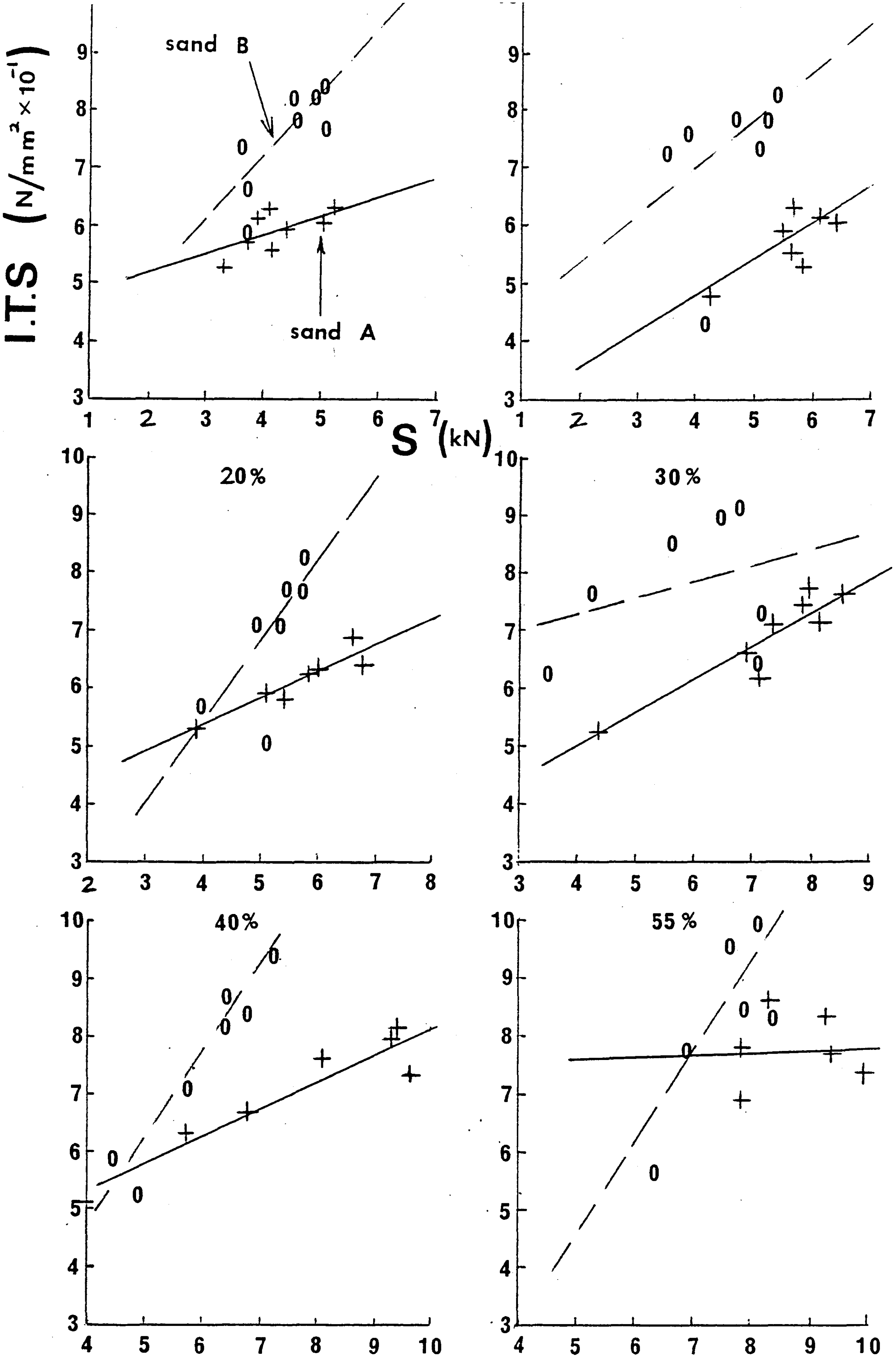
m = Slope of best-fit straight line.

The values of m and c were determined by Linear Regression (see appendix E) and are presented in tables 43 and 44, for sand A and sand B respectively.

Table 43

Sand A - m and c for Linear relationships indicated in figure 32.

Stone Content (% by mass)	0	10	20	30	40	55
SLOPE (m)	0.33	0.62	0.47	0.59	0.45	0.01
INTERCEPT (c)	4.5	2.3	3.5	2.6	3.6	7.7



MARSHALL STABILITY vs INDIRECT-TENSILE STRENGTH

FIG 32

Table 44

Sand B - m and c for Linear relationships indicated in figure 32

Stone Content (% by mass)	0	10	20	30	38	55
SLOPE (m)	1.1	0.80	1.4	0.27	1.5	1.6
INTERCEPT (c)	2.8	3.8	-0.2	6.2	-1.3	-3.4

Although the numerical values of m and c are not in particularly good agreement, a visual assessment of figure 32 indicates a reasonable consistency of the relationship over the Stone Contents considered, for each sand. Consequently when the results for all Stone Contents are considered together, figures 33 and 34, for sand A and sand B respectively, in each case a fairly strong linear relationship is found to exist between Marshall Stability (S) and Indirect-Tensile strength (ITS).

for sand A

$$ITS = (0.46)S + 3.6$$

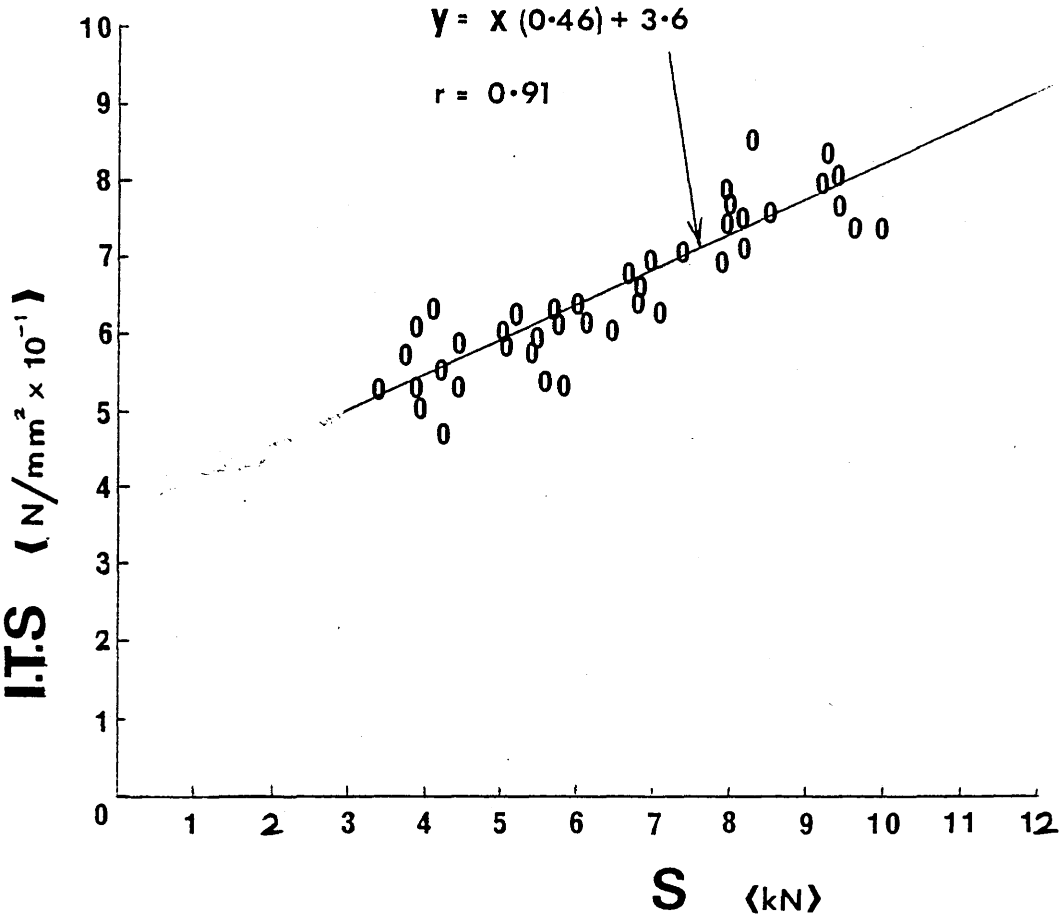
correlation coefficient (r) = 0.91

for sand B

$$ITS = (0.52)S + 4.6$$

$$r = 0.54.$$

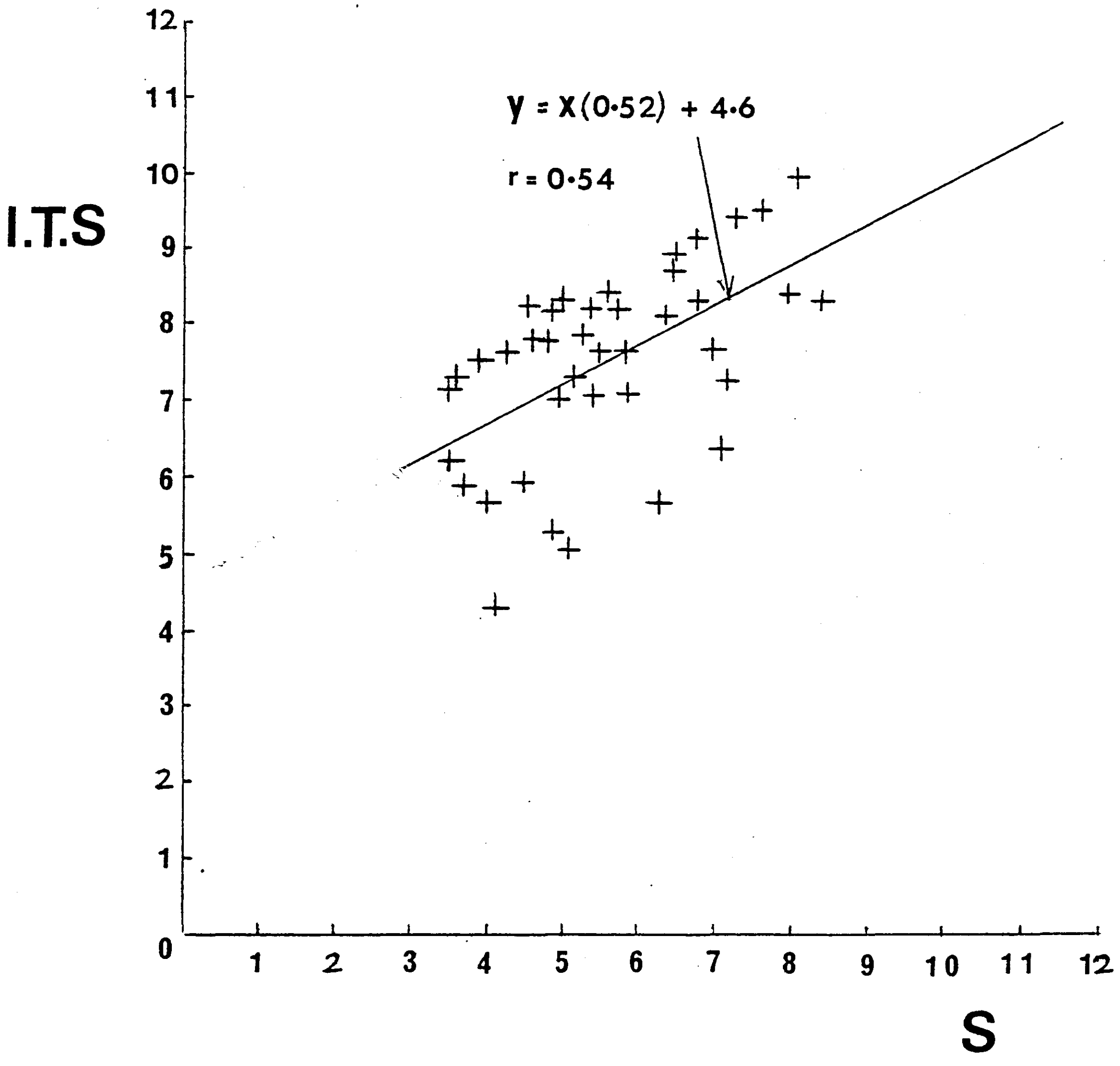
The lower degree of linear association indicated for sand B (r = 0.54), results from the fact that for the lowest binder content considered at each Stone Content, values of ITS are relatively low whilst values of S remain relatively high. This causes the increased scatter in results, and leads one to suppose that if they were ignored, an increased degree of linear association would be apparent.



MARSHALL STABILITY vs INDIRECT-TENSILE STRENGTH : SAND A

(Please note change of symbols from those in fig 32)

FIG 33



MARSHALL STABILITY vs INDIRECT-TENSILE STRENGTH : SAND B

(Please note change in symbols from those in Fig 32)

FIG 34

The relationships derived from the experimental data, indicate, that for both sands, the slopes of the "best-fit" straight lines are approximately equal (0.5), but the intercept values differ considerably.

It would, therefore, appear that the relationship depends upon the nature of the sand. This is best illustrated by referring to figure 35 in which all the experimental data is considered. Although there is slight over-lap, it is clear that the straight-line relationship derived on the basis of the experimental data:

$$ITS = (0.38)S + 4.8 \qquad (r = 0.53)$$

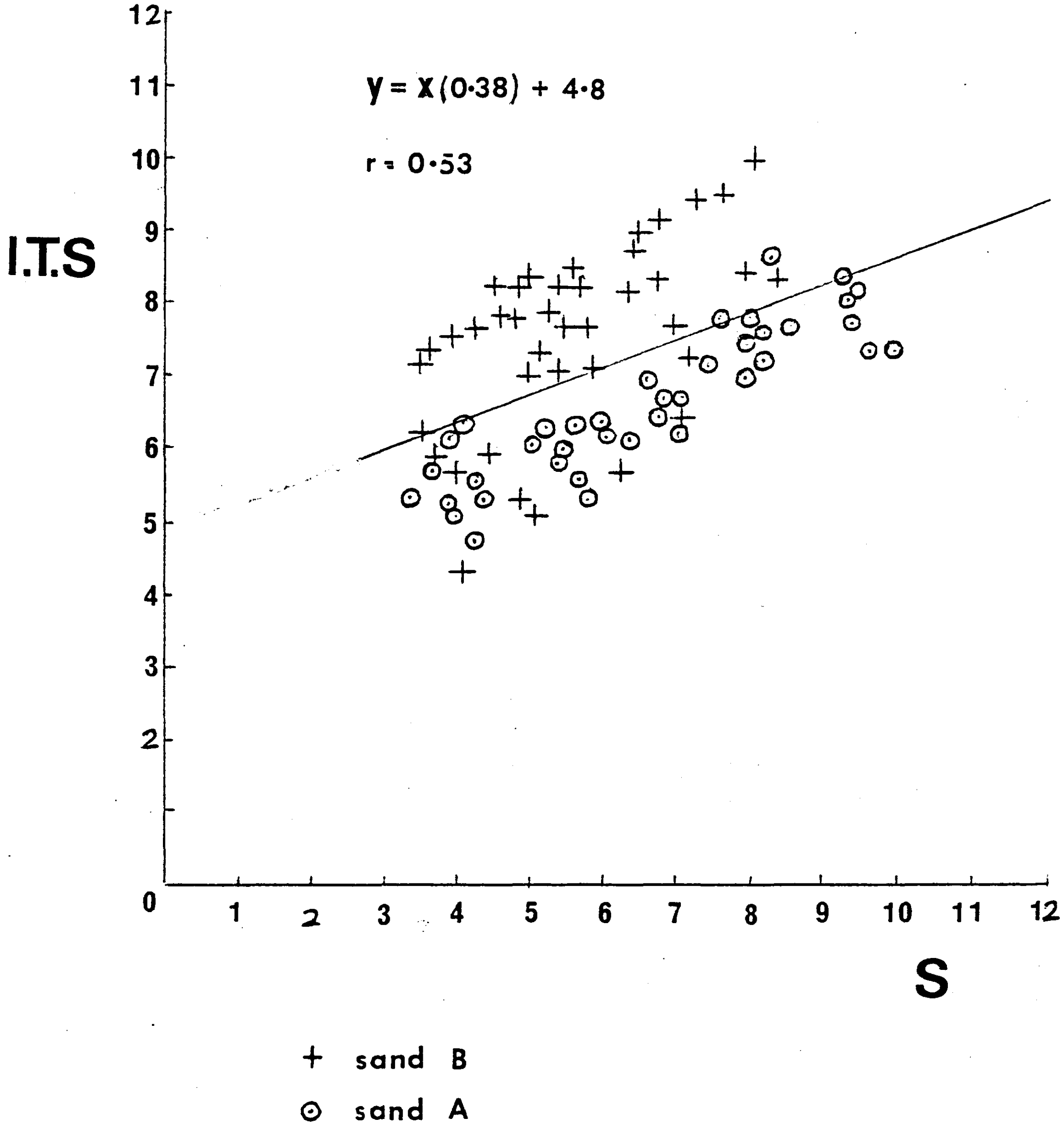
does not describe the situation as adequately, as a separate relationship derived for each sand.

The fact that an approximate Linear relationship exists between Marshall Stability and Indirect-Tensile strength is confirmed by results presented elsewhere.(65)(101)

6.2.3.3 Summary of Conclusions:

(i) Specimens tested in Indirect-tension, failed due to tensile stresses acting perpendicular to the loaded diametral plane. However, the effect on measured strength of the "wedges" formed directly below the loading strips was not determined.

(ii) For H.R.A. mixtures over a range of Stone Contents (0 - 55% by mass) the binder content corresponding to maximum Indirect Tensile Strength was found to be approximately equal to the binder content corresponding to maximum Marshall Stability, for similar mixtures.



MARSHALL STABILITY vs INDIRECT-TENSILE STRENGTH : ALL MIXTURES

FIG 35

(iii) An OBC based upon the mean of the binder contents corresponding to maximum S_M, S_A and ITS, for H.R.A. mixtures over a range of Stone Contents (0 - 55% by mass), was found to be on average less than 0.2% by mass, of binder content different to Marshall OBC.

(iv) A Linear relationship was found to exist between Marshall Stability and Indirect-Tensile strength, for the given H.R.A. mixtures manufactured over a range of binder content, at Stone Content from 0 - 55% by mass.

(v) The latter three findings are considered to be assisted to some degree from the use of the same method of compaction for each test.

(vi) The relationship between Marshall Stability and Indirect-Tensile strength is not general, but depends upon the nature of the fine aggregate (sand) component of the mix.

6.3 Wheel-Tracking Test Results and Comparison with Marshall Results

6.3.1 Comments on Test Procedure

6.3.1.1 Introduction

The development of the apparatus and procedures used in the execution of this test have already been described (5.5). In the following sections, attention will be drawn to several points arising from this and the subsequent use of this test method.

6.3.1.2 Machine Characteristics

As this was a brand new piece of equipment, some time was spent assessing its characteristics.

With the machine set-up for compaction, a 50 kN Load Cell(191) was positioned beneath the roller segment in order to measure the force being exerted. By varying the position of the Load Cell beneath the segment and by adding mass to the load hanger, it was possible to ascertain the following:-

(i) for any given load on the hanger, the force exerted by the roller segment did not vary significantly across its width. This was considered important from the point of view of obtaining as uniform as possible compaction.

(ii) the relationship between mass on hanger and the force exerted by the roller segment. This is expressed in terms of, force per lineal mm of roller width, in figure 36, from which it is possible to determine the mass required to produce a given force per unit width of the roller.

6.3.1.3 Compaction Operation:

Using a single mixture composition (schedule 1A, 30% stone H.R.A. to B.S. 594), the effect of compactive effort upon the density of the resulting specimens was assessed as follows:-

Compactive effort was varied by increasing the load on the hanger, whilst the number of roller passes remained constant (30). Two specimens were produced using each compactive effort, and the density (S_M) and Void content (V_M) of each were determined as described in 5.5.6. Each specimen was then sawn into 16 equal sized blocks (see figure 37) and S_M and V_M were determined for each, as described for Marshall

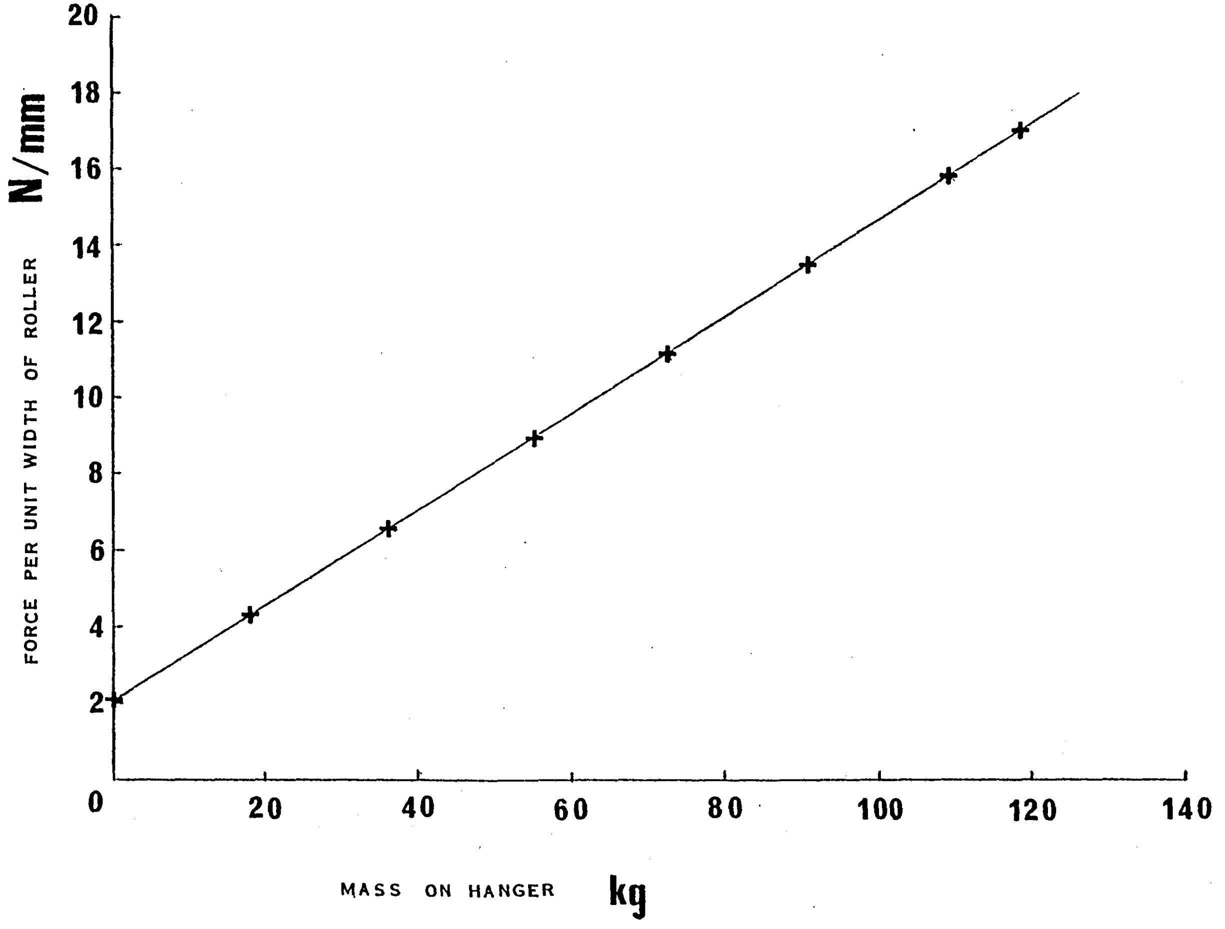
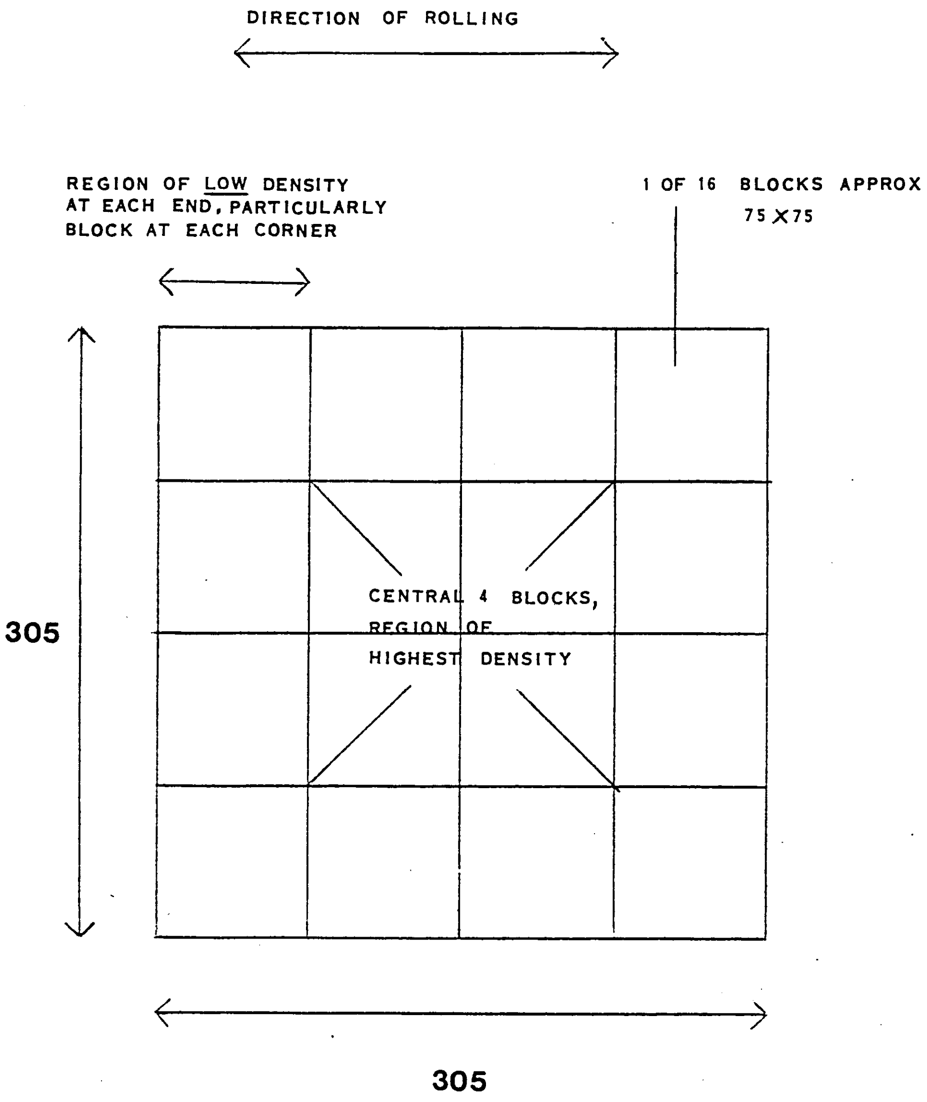


FIG 36

WHEEL-TRACKING MACHINE (Compactive Effort)



DIMENSIONS IN mm

WHEEL - TRACKING TEST SPECIMEN

FIG 37

specimens (5.3.5).

The results obtained indicated, that regardless of compactive effort, a similar distribution of density was apparent in each specimen, see figure 37. The presence of areas of "low" density at each end of specimens, particularly at the corners was not unexpected. Neither was it considered to affect to any great extent the results of Wheel-Tracking tests on such specimens. In fact, in such tests only the central portion of the specimen is subjected to the passage of the loaded wheel, and this area was shown to have a density somewhat greater than that determined for the slab as a whole, see table 45.

Table 45

Specimen Density vs. Compactive Effort, Wheel Tracking Test

Load on Hanger (kg.)	Whole Specimen		Centre*	
	S_M(g/ml)	V_M(%)	S_M(g/ml)	V_M(%)
36.25	2.197	7.7	2.224	6.6
36.25	2.188	8.1	2.231	6.3
54.36	2.192	7.9	2.230	6.3
54.36	2.187	8.1	2.220	6.7
72.50	2.205	7.4	2.224	6.6
72.50	2.190	8.0	2.225	6.6
90.60	2.201	7.5	2.230	6.3
90.60	2.193	7.9	2.228	6.4
108.72	2.177	8.5	2.208	7.2
108.72	2.188	8.1	2.214	7.0
126.84	2.182	8.3	2.207	7.3
126.84	2.178	8.5	2.207	7.3

* mean S_M, V_M for 4 blocks at centre of slab (see figure 36).

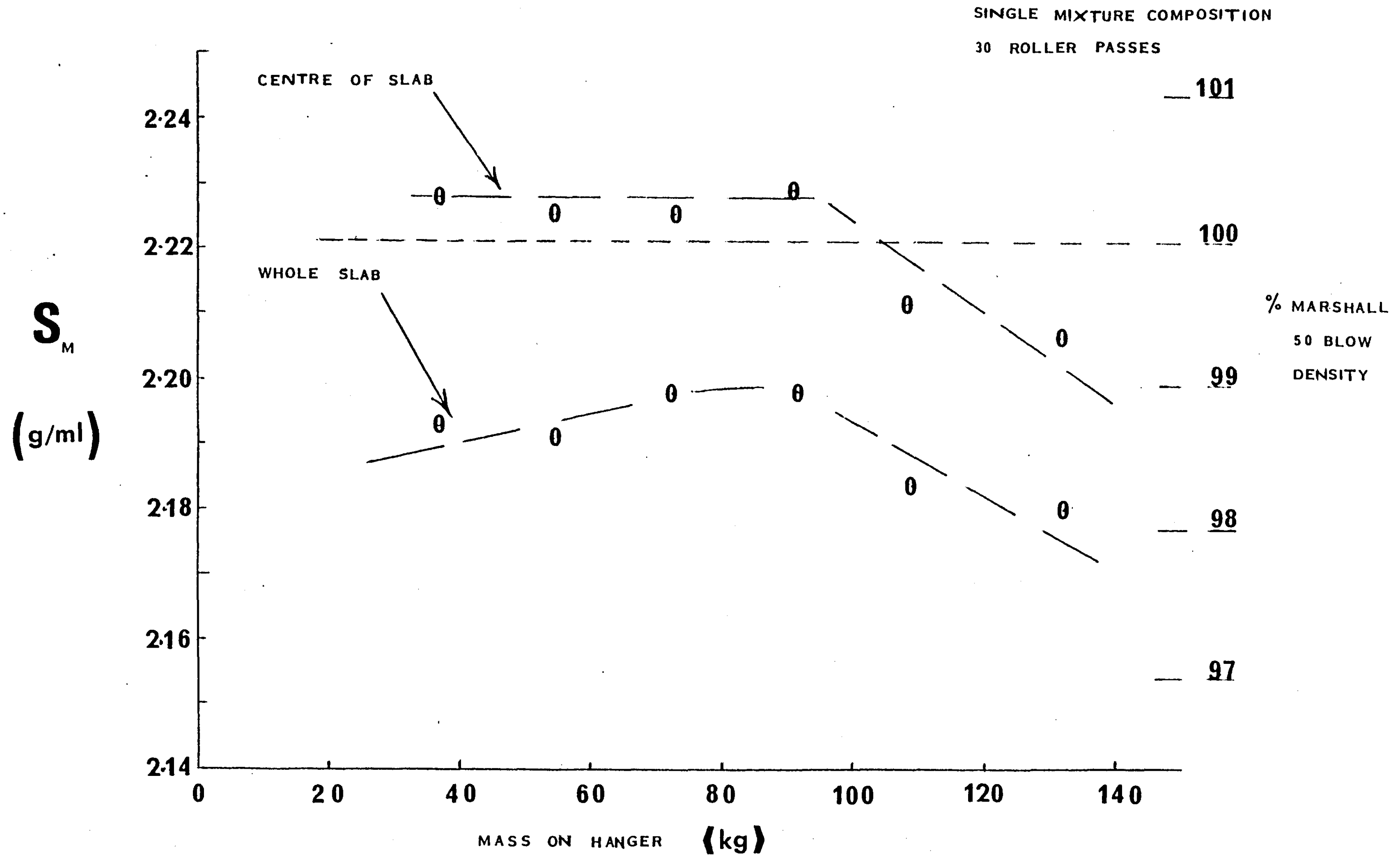
The mean difference between the density of the central 4 blocks and the density of the whole specimen was 0.03 g/ml.

The mean values of S_M for each compactive effort (load on hanger), are presented in figure 38. Compactive effort over the range considered had little effect upon the density of the resulting specimen, although after a certain point S_M begins to decrease sharply. The reason for this is not immediately apparent, although the author considers it to result from a too high compactive effort being applied, a situation analogous to a "foot-print in wet sand". This view is supported by the fact that flushing of the binder was apparent at the surface of such specimens, and that cracking was also apparent.

In selecting a compactive effort to be used for the rest of the investigation, it was thought desirable to achieve densities equivalent to that of Marshall specimens, thus facilitating a direct comparison between Wheel-Tracking and Marshall results. Figure 38, indicates the mean density (S_M) of 4 Marshall specimens comprised of the same mixture. On the basis of this, the central portion of Wheel-Tracking specimens had densities approximately equal to that produced by the Marshall (50 blow) compaction, when using a load on the hanger between 36.25 and 90.6 kg. A compactive effort of 30 passes of the roller, with a load on the hanger of 72.5 kg. was chosen as suitable for specimen manufacture. However, it will be shown later that this arrangement was not effective.

6.3.1.4 Test Results:

A typical Deformation-Time curve, produced during Wheel-Tracking



Specimen Density - Roller Compaction

FIG 38

tests was presented earlier (figure 12). Initially the rate of deformation is high, further compaction of the specimen being the primary cause of this. Eventually, over approximately the last third of the curve the rate of deformation is approximately linear, and the mean rate of increase in rut depth can be determined in mm/hr, see 5.5.7.

As both Tracking Rate (TR) and Rut Depth (RD) are [illegible] important parameters as far as permanent deformation is concerned, it was considered desirable to have some knowledge of the actual rut depth at some point during the test. Three possible alternatives, the rut depth after 100 and 1000 passes of the wheel, and the rut depth at the end of the test were all measured, see figure 12. In this respect, however, the author considers RD_{1000} to be of most use for the following reasons:

(i) RD_{100} occurs during the initial period of rapid, non-uniform deformation of the specimen.

(ii) RD_{END}, i.e. after 45 minutes, this is not reached in cases where the test is terminated prematurely.

The use of RD_{1000} will allow the performance of <u>all</u> mixtures to be assessed in terms of rut depth attained during testing.

6.3.2 Analysis and Presentation of Results:

Wheel-Tracking tests were conducted using the apparatus described in 5.5, according to the procedures set out in appendix B. For each of the Stone Contents considered (table 13), a single specimen was tested at each of several binder contents. The binder contents tested corresponded to those used in the Marshall investigation.

For each specimen tested the following properties were determined in the manner described in 5.5.6 and 5.5.7.

S_M, S_A, V_M, V_A, V_F (see 6.1.2)

Tracking Rate (TR)	mm/hr
Rut Depth after 100 and 1000 passes of the wheel, and after 45 minutes	
RD_{100}, RD_{1000} and RD_{END}, respectively	mm.

For each Stone Content, the values obtained for each specimen are presented in sections D.3.2 and D.3.6 (sand A) and sections D.3.4 and D.3.8 (sand B), of appendix D.

For all Stone Contents, these values were plotted against binder content and smooth curves were drawn through the points. These graphs are presented in sections D.3.3 and D.3.7 (sand A) and sections D.3.5 and D.3.9 (sand B) of appendix D.

6.3.3 Discussion of Results

6.3.3.1 Repeatability:

The degree to which Wheel-Tracking Test results were repeatable within a single laboratory was assessed in the following ways:

(i) 4 specimens containing 30% stone at a single binder content were manufactured and tested in an identical manner, the results are presented in table 46.

Table 46

Repeatability - Wheel-Tracking Test Results (single mixture)

Specimen No.	S_M (g/ml)	T.R. (mm/hr)
1	2.205	N/T
2	2.196	3.50
3	2.205	3.65
4	2.196	3.60

N/T = not tested

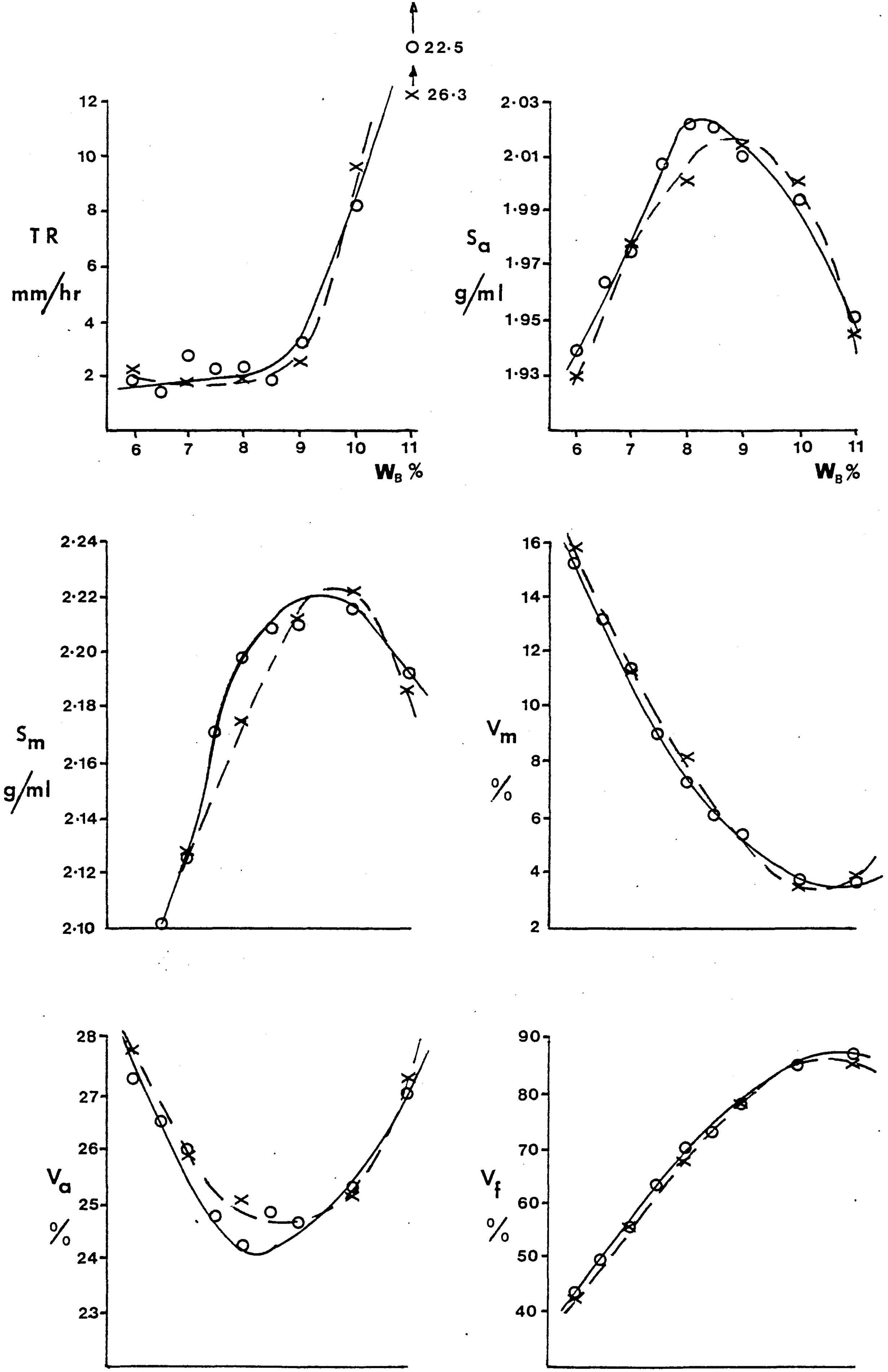
Mean	2.201	3.58
Range	0.009	0.15
Standard Deviation	0.005	0.08

(ii) the results for a duplicate series of specimens, containing sand A and 30% stone, over a range of binder contents are plotted together against binder content (W_B) in figure 39.

The results from both (i) and (ii) indicate a high degree of repeatability and the author is, therefore, confident that the fact that only a single specimen has been tested at each binder content will not unduly effect the accuracy of the results obtained.

6.3.3.2 Optimum Binder Contents determined from Wheel-Tracking Test Results

This part of the investigation set out to determine if an Optimum Binder content, for each stone content, could be defined in terms of the results obtained in the Wheel-Tracking test, in a manner similar to that used in the Marshall Design procedure.



WHEEL- TRACKING TEST (REPEATABILITY)

fig 39

(i) Binder Contents for Maximum S_M and S_A:

Reference to the results presented in sections D.3.3 and D.3.5 of appendix D, indicates that as under Marshall compaction values of S_M and S_A increase as binder content increases, to a maximum value and then decrease. It is, therefore, possible to use the values of the binder contents corresponding to maximum S_M and S_A, to define in part an OBC for each stone content. The values determined in this manner are presented in table 47.

Table 47

Wheel Tracking Test - Optimum Binder Contents
(all figures % by mass)

	SAND A			SAND B		
Stone Content (% by mass)	30	40	55	30	38	55
Binder Content for maximum S_M	9.3	8.6	7.2	6.7	6.3	5.8
Binder Content for maximum S_A	8.2	8.0	6.8	6.4	6.0	5.5
Tracking Rate "Break-point"	8.5	8.0	6.5	6.5	6.0	5.5
Tracking OBC	8.7	8.2	6.8	6.5	6.1	5.5

N.B. the binder contents for maximum S_M and S_A, under roller compaction will be compared with those obtained for similar mixtures under Marshall compaction in section 6.3.3.3.

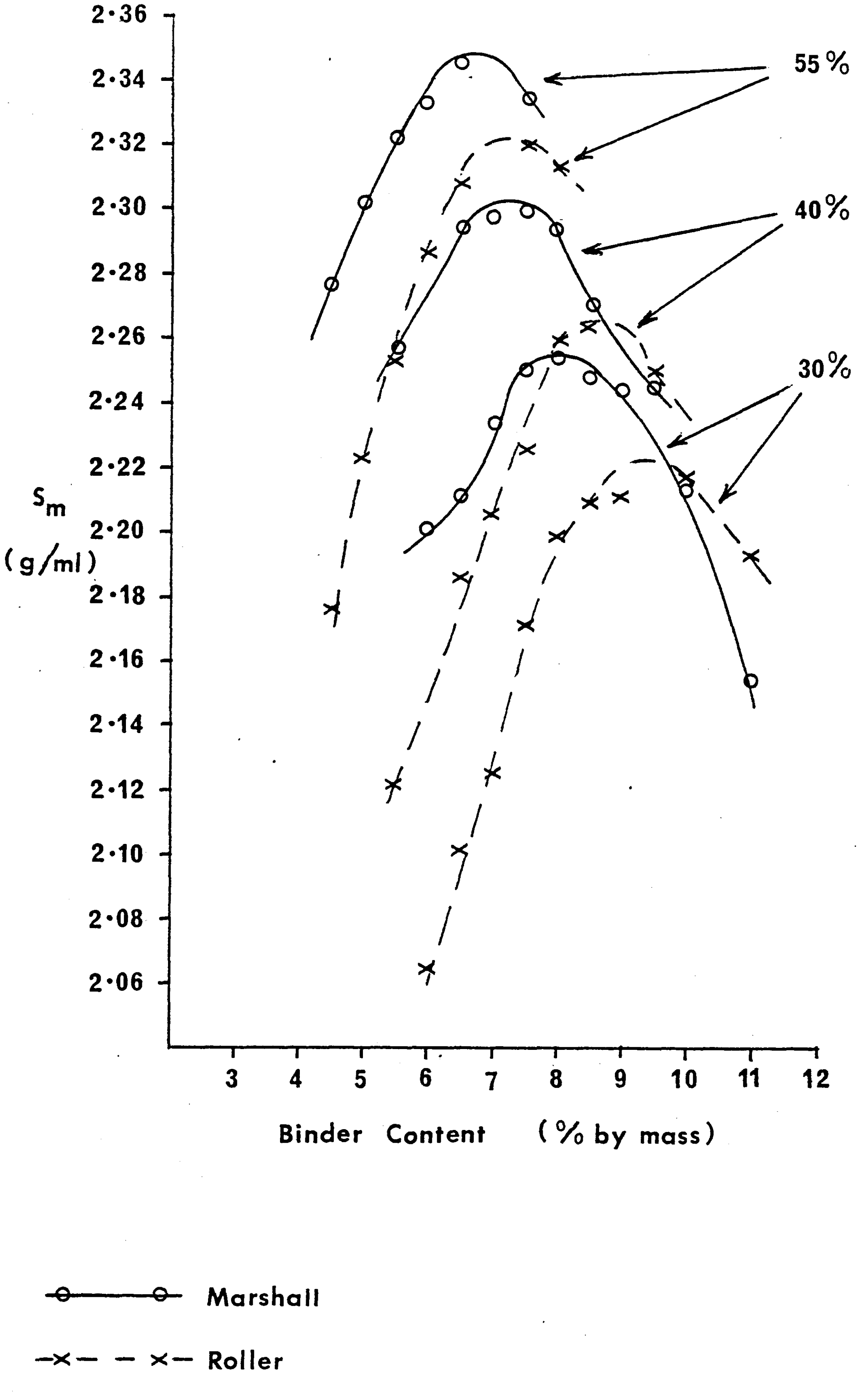
(ii) Binder Contents in terms of Test Performance:

Reference to the results presented in sections D.3.3 and D.3.5 of appendix D indicate that unlike Marshall Stability or Indirect Tensile Strength, the Tracking Rate determined in the Wheel-Tracking test does not pass through a maximum. However, above a certain binder content there is a marked increase in Tracking Rate, the binder content at which this change occurs (break point) can be used as a guide to the optimum binder content of the Mix.(126) The binder contents determined in this manner and the OBC's determined as the mean of this binder content and those corresponding to maximum S_M and S_A are included in table 47.

The OBC's determined in this manner are on average, 1.0% by mass greater than those determined in terms of Marshall test results (tables 24 and 25), for nominally identical mixtures.

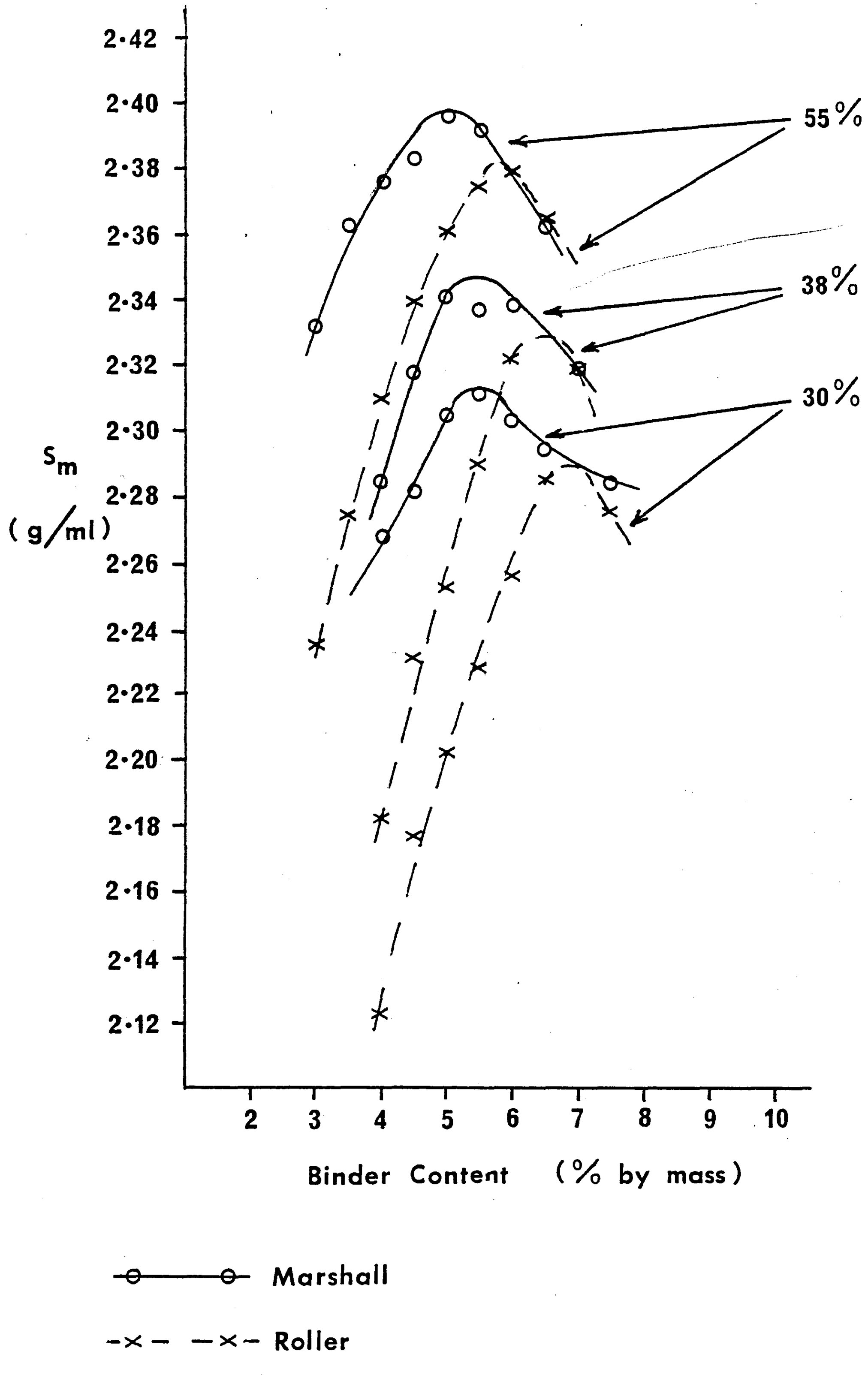
6.3.3.3 Comparison of Marshall and Wheel-Tracking Test Results: Specimens tested by each method had nominally the same composition, but were compacted by different methods and therefore an additional variable other than test method must be considered. Initially, it was hoped that the compactive effort used in producing Wheel-Tracking Test specimens would result in densities equivalent to those of Marshall specimens comprised of the same mix. However, when the density (S_M) of specimens of identical composition, compacted by the different methods are plotted together against binder content (w_B) in figures 40 and 41 for sand A and sand B respectively, it can be seen that at any given binder content, there is a considerable difference between the S_M's of specimens compacted by the two methods. It must, therefore, be concluded that the original assumption regarding the ability to achieve Marshall density was incorrect.

In fact for both sands, at each Stone Content, the relationships between S_M and binder content for specimens produced by roller compaction indicate the following:



Marshall Compaction vs Roller Compaction – Sand 'A'

Fig. 40



Marshall Compaction vs Roller Compaction – Sand 'B'

Fig. 41

(i) The binder content corresponding to maximum S_M is on average, 1.0% by mass greater than that indicated by the corresponding relationships for specimens of nominally identical composition, compacted by the Marshall method.

(ii) The maximum value of S_M is less than that indicated by the corresponding relationships for specimens of nominally identical composition, compacted by the Marshall method.
N.B. reference to sections D.3.3 and D.3.5 of appendix D indicates this is also the case for the relationship between S_A and binder content.

Similar variations are apparent between nominally identical mixtures over a range of binder contents, subjected to differing levels of Marshall compaction.(125) The above observations therefore appear to indicate that in the current investigation the overall level of compactive effort used for roller compaction, was less than that during Marshall compaction. It is this fact, coupled with the inherent differences between the two methods that have resulted in the situation shown in figures 40 and 41.

It should be pointed out at this stage that the values of S_M (for specimens produced by roller compaction) shown in figures 40 and 41, refer to each specimen as a whole. It was reported earlier that the density of the central portion of such specimens was found to be somewhat greater than that of the slab as a whole, and it therefore seems reasonable to suppose that the density of the portion of each specimen actually tested, was in fact greater than indicated in figures 40 and 41. As it was not possible to determine the density of the central portion of each specimen tested, this cannot be proven.

(i) Marshall Stability vs. Tracking Rate:

For each sand considered, the values of Marshall Stability (S) and Tracking Rate (TR) at each binder content (for all stone contents considered) were extracted from the appropriate tables in appendix D, and plotted as shown in figure 42.

The two parameters were found to be related by a Power Function of the form

$$y = ax^{-b}$$

y = Tracking Rate (mm/hr)

x = Marshall Stability (kN)

a and b are constants.

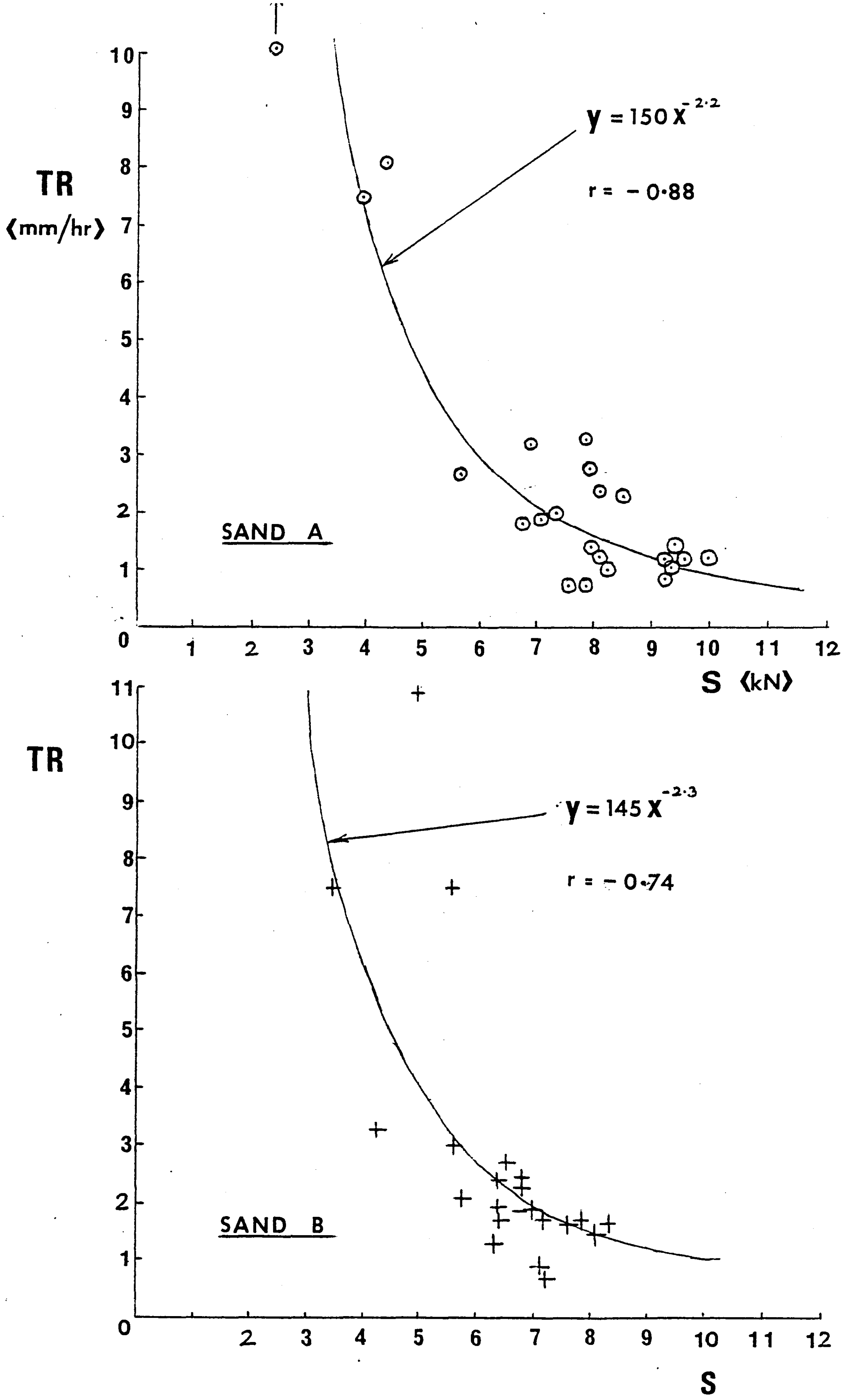
The transformed variables, $\log_{10}x$ and $\log_{10}y$ are linearly related by the equation

$$\log_{10}y = \log_{10}a - b\log_{10}x$$

$\log_{10}a$ = intercept on $\log_{10}y$ - axis

b = slope of best-fit straight line.

The constants a and b, determined by Linear Regression are presented in table 48, and indicate that the relationship is almost identical for both of the sands used.



MARSHALL STABILITY vs TRACKING RATE

FIG 42

Table 48

Relationship between Marshall Stability and Tracking Rate

SAND	Number of Data Points	b	a	r*
A	23	-2.2	150	-0.88
B	20	-2.3	145	-0.74
A and B	43	-2.1	125	-0.82

* Correlation Coefficient (r) (see appendix E)

If all of the data is considered together (figure 43), the recalculated values of a and b (table 48) indicate that

$$y = 125x^{-2.1}$$

(ii) Marshall Quotient vs. Tracking Rate:

The same mixtures as considered previously were used to establish the relationship between Marshall Quotient (Q) and Tracking Rate (TR), which is illustrated in figures 44 and 45.

These two parameters were also found to be related by a Power Function of the form

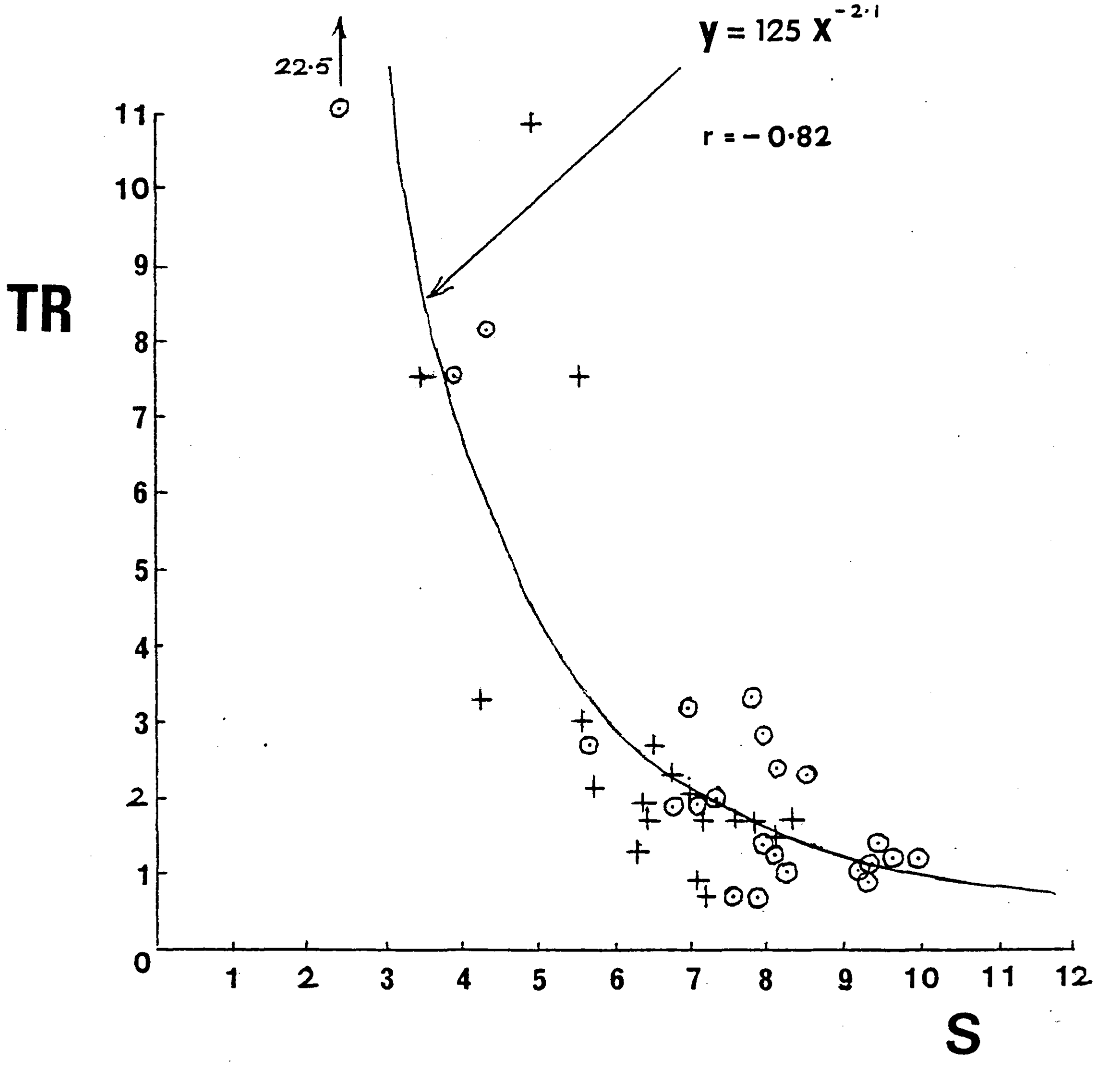
$$y = ax^{-b}$$

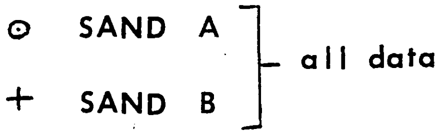
y = Tracking Rate (mm/hr)

x = Marshall Stability (kN)

a and b are constants.

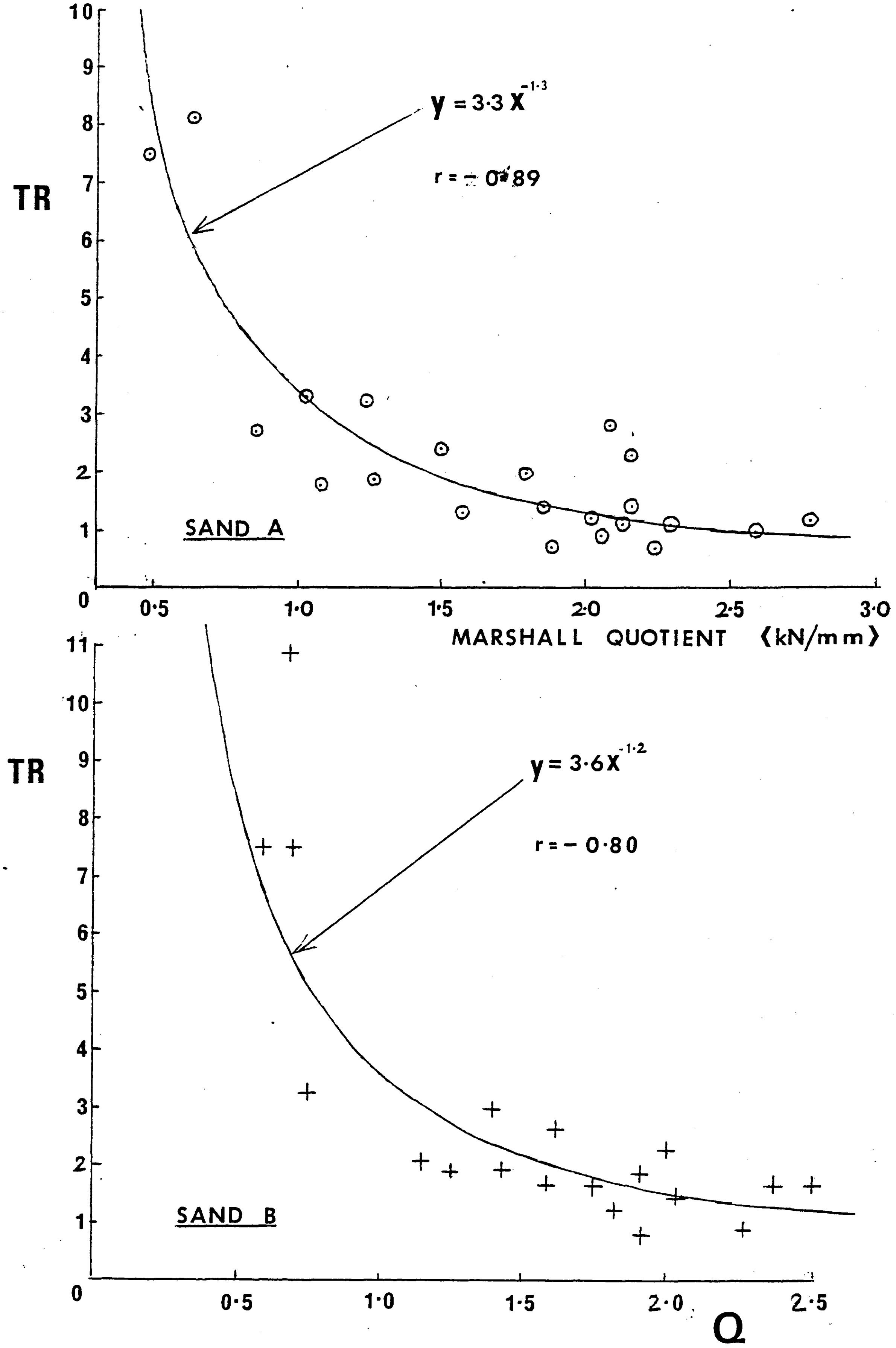
The values of a and b, determined by Linear Regression are presented in table 49.





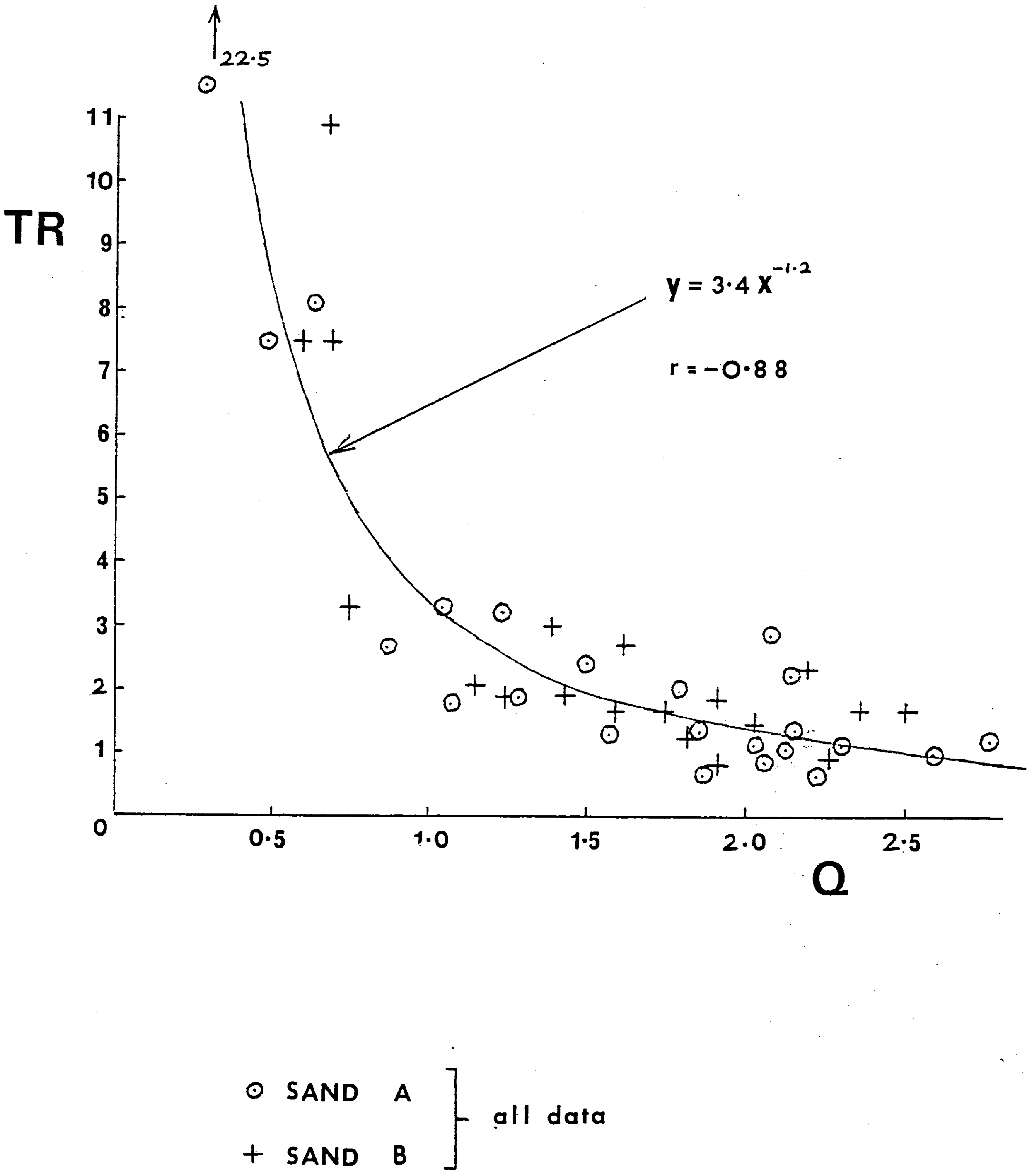
MARSHALL STABILITY vs TRACKING RATE

FIG 43



MARSHALL QUOTIENT vs TRACKING RATE

FIG 44



MARSHALL QUOTIENT vs TRACKING RATE

FIG 45

Table 49

Relationship between Marshall Quotient and Tracking Rate

SAND	Number of Data Points	b	a	r
A	23	-1.3	3.3	-0.89
B	20	-1.2	3.6	-0.80
A and B	43	-1.3	3.4	-0.88

The relationship is again, approximately the same for both sands and based upon <u>all</u> of the mixtures tested

$$y = 3.4x^{-1.3}$$

(iii) Marshall Parameters vs. $R.D._{1000}$:

For all of the mixtures considered previously, the relationships between:

Marshall Stability and RD_{1000}

and Marshall Quotient and RD_{1000}

are illustrated in figures 46 and 47 respectively.

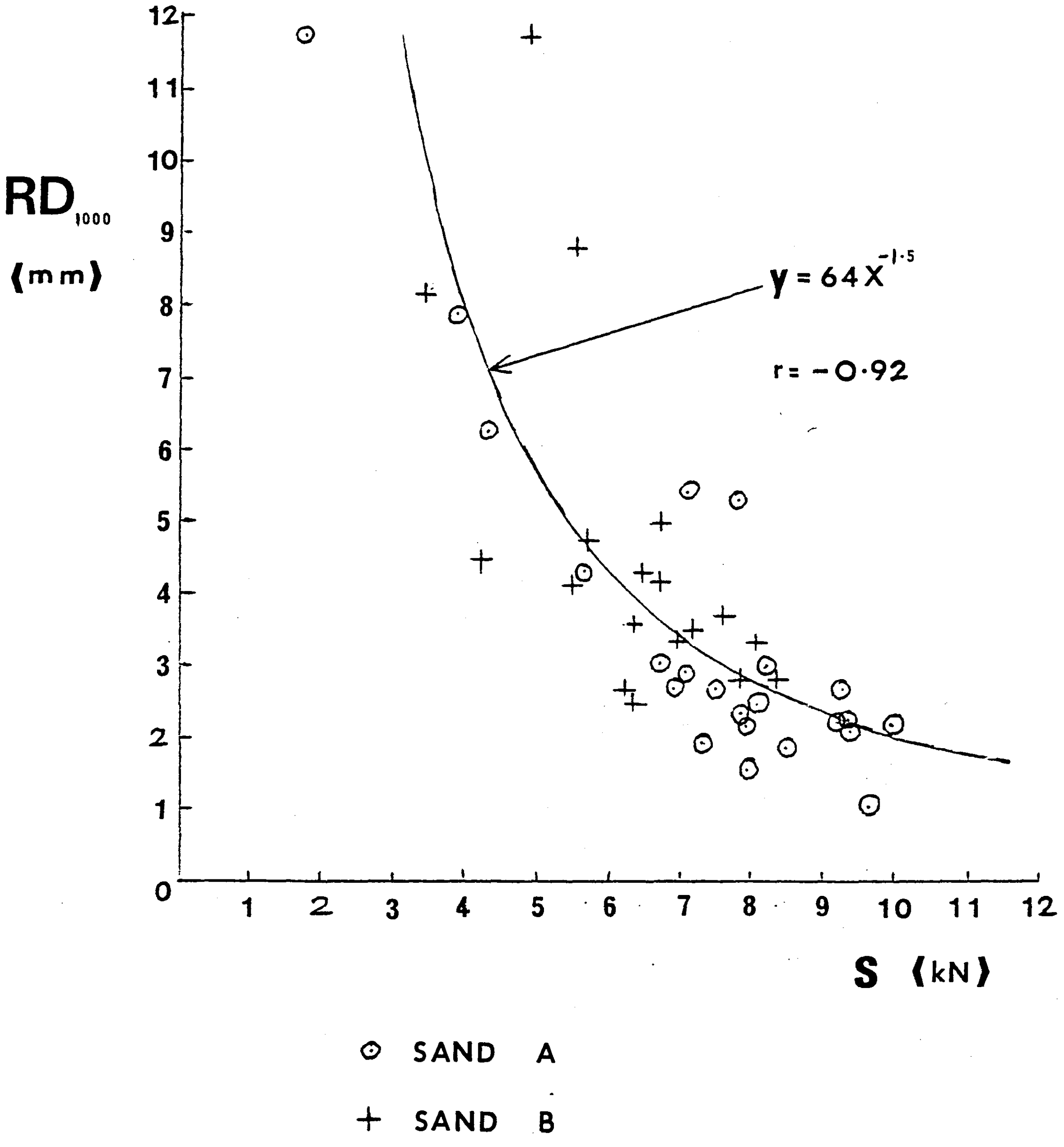
In both cases the parameters were found to be related by a Power Function of the form:

$$y = ax^{-b}$$

In each case, for $RD_{1000} = y$, the values of a and b, determined by Linear Regression indicate the following:

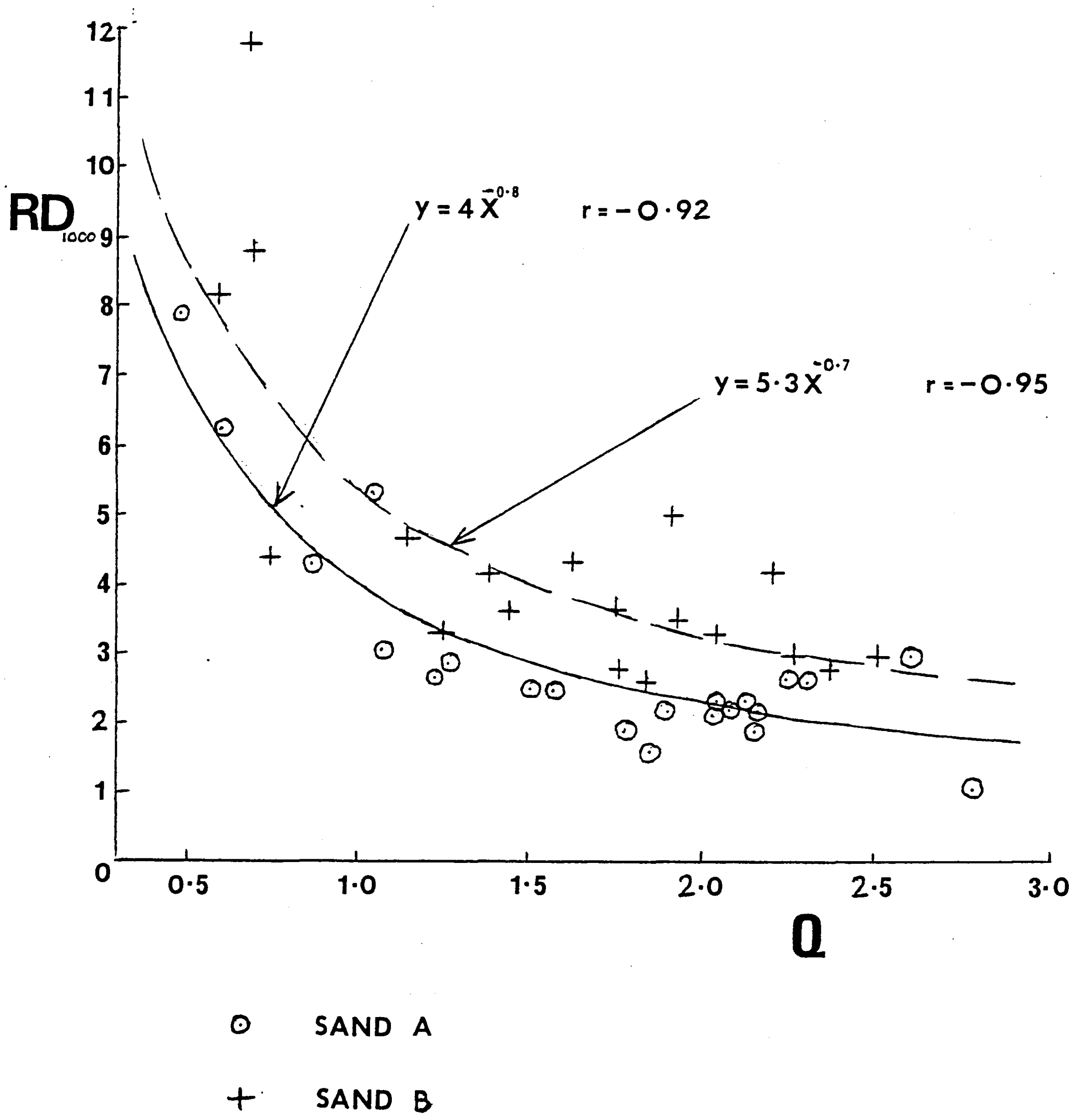
(a) a single relationship between S and RD_{1000}, for <u>all</u> mixtures tested:

$$y = 64x^{-1.5}$$



MARSHALL STABILITY vs
RUT DEPTH AFTER 1000 PASSES

FIG 46



MARSHALL QUOTIENT vs
RUT DEPTH AFTER 1000 PASSES

FIG 47

(b) a separate relationship between Q and RD_{1000}, depending upon the type of sand:

for mixtures containing sand A

$y = 4x^{-0.8}$

for mixtures containing sand B

$y = 5.3x^{-0.7}$

The latter (b), is considered by the author to be a reflection of the fact that mixtures containing sand A tended to exhibit higher Flow values and lower values of RD_{1000}, than mixtures containing sand B.

(iv) General Discussion of Relationships:

It is clear that on the basis of the relationships established, both Marshall Stability and Marshall Quotient are related to deformation (as measured in the Wheel-Tracking Test).

Table 50 indicates that in all cases the degree of association between the transformed variables ($\log_{10}x$ and $\log_{10}y$), as measured by the Correlation Coefficient (r) is high.

Table 50

Correlation Coefficients for relationships between Marshall parameters and Wheel-Tracking Test parameters.

Relationship between	Correlation Coefficient (r)
$\log_{10}S$ and $\log_{10}TR$	-0.82
$\log_{10}Q$ and $\log_{10}TR$	-0.88
$\log_{10}S$ and $\log_{10}RD_{1000}$	-0.92
$\log_{10}Q$ and $\log_{10}RD_{1000}$	-0.84*

*mean value of relationships derived for sand A and sand B.

Although the degree of association is slightly increased for relationships where Wheel-Tracking performance is quantified in terms of RD_{1000}, the author considers these relationships in terms of Tracking Rate (TR) to be more important in the light of extensive correlations between this and actual road performance.(92)(124)

Considering these relationships (in terms of TR) in more detail, over the range of mixtures tested it appears that:

(a) Tracking Rate is relatively unaffected by changes in Marshall Stability (or Marshall Quotient) above a certain level.

(b) Below a certain value of Marshall Stability (or Marshall Quotient), Tracking Rate begins to increase rapidly.

In practical terms this can be interpreted as indicating that little advantage (over normal mixtures) will be gained (in terms of improved resistance to deformation) from the use of mixtures having exceptionally high values of Marshall Stability or Marshall Quotient. Further, the value of Marshall Stability or Marshall Quotient corresponding to the point at which Tracking Rate begins to increase rapidly could be used as a criterion to ensure adequate mixture performance (in terms of resistance to deformation).
In this respect, the results presented (figures 43 and 45) indicate minimum values of 7kN and 1.5 kN/mm for Marshall Stability and Marshall Quotient respectively. The latter value is in good agreement with values proposed by Marais(65) and Brien,(202) for climatic conditions similar to those found in the U.K.

When talking in the above terms however, it is necessary to consider the degree of "confidence" that can be placed on these relationships. To this end, consideration of the Correlation

Coefficients (r) indicated, may not be enough. As reference to figures 43 and 45 reveals, there is considerable scatter of the data about the "best-fit" curve in each case. In the author's opinion this high degree of scatter may be a result of the fact that:

(a) only a low degree of confidence can be placed on the mean values of Marshall Stability and Marshall Quotient, determined for duplicate specimens. (See 6.1.3.1)

(b) only a single specimen was tested in order to establish values of Tracking Rate for each mixture considered.

However, in spite of this the author concludes that both Marshall Stability and Marshall Quotient are strongly related to deformation (as measured in the Wheel-Tracking Test), although the exact relationship may be, to some extent "masked" by the scatter of the data.

6.3.3.4 Summary of Conclusions:

(i) The compaction sequence used in this investigation, for the production of Wheel-Tracking Test specimens was unable to reproduce the densities achieved under Marshall Compaction, for nominally identical mixtures.

(ii) It is possible to define an optimum binder content for mixtures tested under the conditions of the Wheel-Tracking test, as the mean of the binder contents corresponding to maximum S_M, maximum S_A and the point at which TR begins to rise sharply.

(iii) Optimum binder contents determined in the above manner were found to be on average, 1.0% greater than those determined by the Marshall method, for nominally identical H.R.A. mixtures containing between 30 and 55% by mass of stone.

(iv) For H.R.A. mixtures containing between 30 and 55% by mass of stone, a relationship of the form

$$y = ax^{-b}$$

was found to exist between the following parameters:

Marshall Stability and Tracking Rate
Marshall Quotient and Tracking Rate
Marshall Stability and RD_{1000}
Marshall Quotient and RD_{1000}.

(v) All of the above relationships, except that between Marshall Quotient and RD_{1000}, were found to be independent of the type of fine aggregate (sand) used in the mixture.

(vi) Despite the scatter of the experimental data, both Marshall Stability and Marshall Quotient are strongly related to deformation (as measured in the Wheel-Tracking Test).

6.4 Optimum Binder Content in Relation to Mixture Properties

From a consideration of all results obtained in this investigation, it is apparent that irrespective of the type of compaction used, the physical properties of mixtures produced vary with respect to binder content in a similar manner.

As binder content is increased:-

S_M, increases to a maximum then decreases

S_A, increases to a maximum then decreases

V_M, decreases to a minimum then begins to increase

V_A, decreases to a minimum then increases

V_F, increases to a maximum then begins to decrease.

For each stone content, the binder contents corresponding to maximum S_A, and minimum V_A have been determined and are presented in tables 51 and 52, for Marshall and Roller compaction respectively.

Following a similar procedure the values of S and TR were found to vary with respect to binder content in a similar manner, for each stone content considered. As binder content is increased:-

S, increased to a maximum then decreases

TR, remains relatively unchanged initially, then begins to increase rapidly.

For each stone content, the binder contents corresponding to maximum S and the point at which TR begins to increase, are presented in tables 51 and 52 respectively.

Table 51

Mixture Properties - Marshall Compaction

(all figures % by mass)

Stone Content (% by mass)	0	10	20	30	40*	55	
Binder Content for Maximum S_A	11.2	9.8	8.0	7.5	6.7	5.9	SAND A
Binder Content for Minimum V_A	10.8	9.4	8.0	7.2	6.3	5.8	
Binder Content for Maximum S	12.0	10.7	8.7	7.5	6.7	5.9	
Marshall OBC	11.8	10.4	8.7	7.6	6.9	6.2	
Binder Content for Maximum S_A	7.1	6.2	6.2	5.1	5.0	3.8	SAND B
Binder Content for Minimum V_A	7.1	6.3	6.1	5.0	5.0	4.2	
Binder Content for Maximum S	6.8	6.5	5.6	4.5	4.4	4.3	
Marshall OBC	7.3	6.5	6.1	5.0	4.9	4.3	

* 38% by mass Stone for mixtures containing sand B

Table 52

Mixture Properties - Roller Compaction

(all figures % by mass)

	SAND A			SAND B		
Stone Content (% by mass)	30	40	55	30	38	55
Binder Content for Maximum S_A	8.2	8.0	6.8	6.4	6.0	5.3
Binder Content for Minimum V_A	8.2	7.7	6.7	6.6	6.0	5.2
Binder Content for Break Point TR	8.5	8.0	6.5	6.5	6.0	5.5
Wheel-Tracking OBC	8.7	8.2	6.8	6.5	6.1	5.5

The results presented in tables 51 and 52 indicate that the binder contents corresponding to maximum S_A and minimum V_A are approximately equal in each case. This binder content therefore represents, for that level of compaction, the point at which the aggregate structure is most densely packed. Further it is suggested, from table 52, that the binder content corresponding to the point at which TR begins to increase, coincides with that at which the aggregate structure is most densely packed, (i.e. maximum S_A - minimum V_A). It, therefore, appears that if binder content is increased beyond this point, the effective aggregate density (S_A) will begin to decrease as the aggregate particles are forced apart by the increasing volume of binder and consequently TR begins to rise as the additional binder begins to act as a lubricant, so destroying the inter-particle friction.

The situation regarding the binder content corresponding to maximum S (table 51) is less clear, although it is suggested that this too corresponds closely to the binder content at which the aggregate structure attains its densest packing. As binder content is increased beyond this point, Stability begins to decrease as a result of decreasing cohesion between the aggregate particles.

It has already been shown, that for both methods of compaction, the binder content corresponding to maximum S_A, for any given mixture, is less than that corresponding to maximum S_M by approximately 1.0%. Therefore, when the OBC's, based on the mean of the binder contents corresponding to maximum S_M, maximum S_A and maximum S (or the point at which TR begins to rise) are considered, they are found to be fractionally greater than the binder content corresponding to maximum S_A and minimum V_A (see tables

51 and 52). It would, therefore, appear that OBC's selected in this manner correspond closely to the binder content at which the aggregate structure will attain its densest packing, under the given level of compaction.

It would also appear that under conditions of Marshall compaction, sand asphalt mixtures are considered to be carrying the maximum usable amount of binder, at a binder content corresponding to that for maximum Stability.(67) However, it is further suggested that in the practical situation, the level of compaction achieved will be somewhat less and, therefore, the most suitable binder content will be higher, possibly that corresponding to maximum S_M (under Marshall Compaction.)(67)

If the latter situation is true, this leads the author to consider that the OBC's based on Wheel-Tracking Test results, (determined in the current investigation) might correspond to those binder contents that would lead to optimum performance of the respective mixtures in the practical situation. However, if this is not the case, and the level of compaction achieved in practise corresponds to that under Marshall Compaction, the results presented (6.1.3.1) would tend to indicate that H.R.A. mixtures based upon the B.S. 594 Design method, tend to be overfilled bitumen-aggregate mixtures. This finding would tend to agree with opinions expressed elsewhere.(66)

6.5 Mixture Properties in Relation to Resistance to Deformation

Mix Design Procedures are employed in an attempt to ensure the production of the most economic mixture, having an acceptable level of resistance to deformation in a given situation. Typically, the Design procedure employed may be considered as a two stage operation:

(i) the selection of an "optimum" mixture composition (usually an optimum binder content) for the constituent materials being considered

(ii) a check is then made to ensure that the mixture composition selected above, meets certain requirements (Design Criteria) regarding mixture "Strength" and durability.

In this context, the relationship between OBC and mixture properties has already been discussed (6.4), and attention will now be turned to the relationship between mixture properties (measured "strength") and in particular resistance to deformation.

In the U.K., design criteria for H.R.A. wearing course mixtures were introduced from April, 1980.(20)(21) As the Marshall H.R.A. Mix Design procedure (B.S. 594(7)) requires the determination of an OBC for the mortar portion of the mix only, these Design Criteria are also, only related to the mortar. In order to ensure adequate resistance to deformation, mortar mixtures at their OBC are required to attain a minimum value of Marshall Stability (see table 4), depending upon anticipated traffic volumes. It is apparent that using this approach, it is not always easy to obtain natural sands capable of meeting these requirements, particularly for the highest traffic category.(58)

With a view to improving upon the present design procedure, a logical step would seem to be to determine the OBC for the Total-Mix (coarse-aggregate included) and to specify Design Criteria in terms of the Total Mix. This approach appears to have numerous advantages (discussed later) and may well make it easier to design mixtures to meet the Design Criteria specified.

During the present investigation, a strong relationship was found to exist between Marshall parameters (S and Q) and Wheel-Tracking rate, for H.R.A. mixtures containing between 30 - 55% Stone.
On the basis of this the author intends to suggest possible Design Criteria, in terms of the Total-Mix, for different traffic volumes.
It was reported earlier that on the basis of extensive laboratory-road correlations, recommended maximum Wheel-Tracking rates had been proposed,(124) (table 11) for different traffic volumes.
Using these figures, values of Marshall Stability (S) and Marshall Quotient (Q) corresponding to the maximum Wheel-Tracking rates for a given traffic category have been determined from figures 43 and 45, and are presented in table 53.

Table 53

H.R.A. Design Criteria - Total Mix:

No. of Commercial Vehicles per lane per day	Maximum Tracking Rate (mm/hr)	From Figures 43 and 45		Implied FLOW	SUPPLY VALUES		
		S(kN)	Q(kN/mm)	F(mm)	S(kN)	Q(kN/mm)	F(mm)
1500	8	3.5	0.5	7.0	4.5	0.7	5.4
3000	4	5.0	0.9	5.5	6.3	1.2	4.4
6000	2	7.5	1.5	5.0	9.4	2.0	4.0

For each set of corresponding values of S and Q, an "implied" Flow (F) value has been calculated

$$\text{Implied Flow (F)} = \frac{S}{Q} \text{ mm}$$

and is included in table 53. The above values of S and Q are suggested minimum values, to ensure adequate resistance to deformation for that particular category of traffic.

N.B. these suggestions are made only on the basis of results obtained during the current investigation.

It should be remembered at this point, that when supplying material to a given specification, the material is often produced to a higher quality so as to take account of compositional variation, etc. which may otherwise cause it to fall outside of the specification. In calculating safety margins for this purpose, average values of Reproducibility (R%) for S, Q and F are required.

For a 1 in 20 risk that the material is outside specification, Hills(58) has considered the calculation of "supply" values as follows:-

Safety Margin (M) = 0.6 x R

from table 6, reproducibility for Stability (R) = 47%

hence

M = 0.6 x 47 = 28.2%

if

Minimum Stability (S) = 3.5 kN

then

"Supply" Stability = 3.5 x 1.282

= 4.5 kN (approx.)

"Supply" values for S, Q and F have been calculated in this way using the appropriate values of R, from table 6, and are presented in table 53.

Results presented by Hills(58) suggest that typical, designed, 30% stone H.R.A. mixtures would be more likely to meet the design criteria contained in table 53, compared to the proportion of typical mortar mixtures (containing the same sands as the 30% mixes) meeting the present criteria. In addition, the author also considers it to be easier to make adjustments in the composition of the Total-Mix, in order to meet Design Criteria, than it is to tackle the problem by considering the mortar portion of the mix in isolation. Further, if the reproducibility of Marshall Test results could be improved, as clearly it must, then the "supply" values (table 53) would be somewhat reduced, with the possibility that an increased range of mixtures would then be considered suitable for use.

The preceding discussion has considered Mix Design from the point of view of ensuring adequate resistance to deformation. The Total-Mix design procedure, has however further advantages in that it would allow specification of requirements regarding

(i) the void content of mixtures
(ii) the degree of compaction to be achieved.

Percentage Voids in the Mix (V_M) is usually specified in terms of minimum and maximum values. The former is to ensure that there is sufficient void space within the compacted mix to allow slight expansion of the binder, due to additional compaction under traffic and increases in temperature, without producing flushing and the associated decrease in resistance to deformation. The latter (maximum V_M) is to ensure that void content is sufficiently low, so that the mixture remains impermeable to air and water. Although it would be possible to specify upper and lower limits, in terms of the mortar only, for use in conjunction with the present design procedure for selecting OBC,(7) a much more logical approach would be to consider the Void Content of the Total-Mix thereby ensuring that the actual mixture laid on the road had adequate durability. For H.R.A. Mixtures containing 30% stone, a lower limit on V_M is usually considered to be about 2%,(65) while the upper limit could be as high as 8 or 9%(202) without causing the mixture to be permeable. A typical range of V_M which might be specified is 3 - 5%,(203) although the author considers the upper limit might be somewhat restrictive.

The degree to which a mixture is compacted can have a significant effect upon the following:

(i) its resistance to deformation

(ii) the binder content required to produce optimum performance

(iii) its air void content and consequently its durability.

The composition of a mixture designed in the laboratory, has been selected to optimise certain properties of that mixture, but is this only the case for the particular degree of compaction achieved in the laboratory. A mixture having such a composition, laid on the road will have very different properties if not compacted to the same degree as in the laboratory. The problem therefore is to ensure that as-constructed density approximates laboratory density. Many countries specify that the density of cores taken from as-constructed pavements, should be a given percentage of laboratory density (usually in terms of Marshall Compaction). A typical requirement for dense bituminous surfacings is an as-constructed density of 98% Marshall density (in the laboratory).

The only way such criteria could be applied to H.R.A., is if part if not all of the Design procedure is carried out in terms of the Total Mix.

6.6 Laboratory - Road Correlations

In the practical situation, the optimum mixture composition from a performance point of view is dependent upon many factors:- degree of compaction, skidding resistance, fatigue resistance and resistance to deformation, etc. The optimum mixture composition from the point of view of each must be considered, and a compromise made between the requirements of each. The optimum mixture composition in terms of in-service performance, can only be determined by studying the behaviour of in-service pavements.

As stated earlier (chapter 3), it was intended, as part of the current investigation, to carry out a comparison in terms of resistance to deformation, so that laboratory OBC's could be compared with in-service behaviour. However, no data has yet been published regarding the performance of the test sections laid on the A33 at Winchester,(59) and hence this comparison has not proved possible. The author has access to only limited data(204) on the early performance of these sections and considers it to be insufficient to enable any meaningful inferences to be made or conclusions to be drawn at this stage.

7. MAIN CONCLUSIONS

7.1 Introduction

The following sections contain a summary of the principal findings and conclusions, related to each aspect of the work conducted during the course of the current investigation.

7.2 The Marshall Test

7.2.1 Test Procedure

(i) Using the procedures developed during this work, test specimens, having within close tolerances, the desired binder content and aggregate gradation, could be produced.

(ii) No practical problems were encountered using the Load Cell-Chart Recorder system for the determination of Stability and Flow values.

(iii) Provided a testing machine capable of applying load at a constant-rate of strain is used, there is no reason to doubt the validity of Flow values determined in the above manner.

(iv) No practical problems were encountered when the testing procedure was extended to H.R.A. mixtures containing up to 55% by mass of stone.

7.2.2 Repeatability and Reproducibility

(i) For H.R.A. mixtures containing up to 55% by mass of stone, the mean difference between duplicate test runs (over a range of binder content, for nominally identical mixtures, in a single laboratory) was found to be:

between the binder contents corresponding to

maximum S_M = 0.2%

between the binder contents corresponding to maximum S_A = 0.25%

between the binder contents corresponding to maximum S = 0.4%

between the maximum values of Marshall Stability (S) = 0.75 kN

between Marshall OBC's = 0.2%.

(ii) A very limited study was carried out to assess the reproducibility of test results (for nominally identical mixtures) between two laboratories (Sheffield and E.R.C.A.), insufficient results were obtained to allow any sound conclusions to be drawn.

(iii) Taking the above results at face value, the reproducibility at first sight would appear to be good. The author suggests that this is due to the efforts made to duplicate the equipment and procedures used in the two laboratories. However, more work is required to ascertain if this is the case.

7.2.3 Method of Measurement of Stability:

(i) The method used to measure Stability was found to have a pronounced effect upon the results obtained for nominally identical mixtures.

(ii) For duplicate tests on nominally identical H.R.A. mixtures containing up to 40% by mass of stone, over a range of binder contents, it was found that the value of the binder content corresponding to maximum S and value of maximum Stability (S), for the mixtures tested using the Load Cell were on average 1.0% and 1 kN respectively, greater than the corresponding values for mixtures tested using the Load Ring, in place of the Load Cell.

(iii) For H.R.A. mixtures containing 0 and 30% by mass stone, at a single binder content, the difference between the values of Stability determine by the Load Cell and the Load Ring, was found to be significant at the 5% level.

7.2.4 Results Obtained for H.R.A. Mixtures:

(i) For H.R.A. mixtures containing between 30 and 55% by mass of stone, the Optimum Binder Content determined as the mean of the binder contents corresponding to maximum S_M, S_A and S, are approximately inversely proportional to Stone Content and closely related to the OBC of the mortar.

(ii) On average, for stone contents between 30 and 55% by mass, the OBC's determined in the above manner, are 0.7% by mass less than the Target Binder Contents selected according to the B.S. 594 design procedure.

7.3 The Indirect-Tensile Test

7.3.1 Test Procedure

(i) Specimens of H.R.A. containing up to 55% by mass of stone, tested by this method, failed due to tensile stresses acting perpendicular to the loaded diametral plane.

(ii) The effect on measured strength, of the "V" shaped wedges which form directly beneath the loading strips during testing was undetermined.

7.3.2 Results Obtained for H.R.A. Mixtures:

(i) For H.R.A. mixtures containing up to 55% by mass of stone, the binder content corresponding to maximum ITS, was found to be approximately equal to that corresponding to maximum S, for nominally identical mixtures tested by the Marshall method.

(ii) OBC's determined as the mean of the binder contents corresponding to maximum values of S_M, S_A and ITS were approximately equal to the Marshall OBC's determined for nominally identical H.R.A. mixtures containing up to 55% by mass of stone.

(iii) The apparent agreement between the OBC's determined by the Marshall and Indirect Tensile methods, is considered by the author to be partly due to the fact that the same method of compaction was used in both tests.

7.4 Relationship between Marshall Stability and Indirect-Tensile Strength

(i) For H.R.A. mixtures containing up to 55% by mass of stone, a strong linear relationship of the form

$$y = mx + c$$

was found to exist between Marshall Stability (x) and Indirect Tensile Strength (y).

(ii) The relationship between Marshall Stability and Indirect Tensile Strength was found to be dependant upon the type of sand contained in the mixtures.

(iii) For the two sands studied, the slopes of the best-fit straight lines through the experimental data were approximately equal in both cases, however the position of these lines differed considerably due to differences between the two sands.

7.5 The Wheel-Tracking Test

7.5.1 Test Procedure:

(i) Specimens produced by roller compaction were found to have a non-uniform density distribution. In particular, the density of the central portion of specimens was somewhat greater than the density of the specimen considered as a whole.

(ii) The compactive effort used throughout this investigation was unable to reproduce (for nominally identical mixtures) the degree of compaction produced by the Marshall method.

7.5.2 Results Obtained for H.R.A. Mixtures:

(i) For H.R.A. mixtures containing between 30 and 55% by mass of Stone, compacted over a range of binder contents, using roller compaction, the binder contents corresponding to maximum S_M and S_A were found to be on average 1.0% greater than those for nominally identical mixtures, compacted by the Marshall method.

(ii) It was possible to define an OBC in terms of Wheel Tracking test results, as the mean of the binder contents corresponding to maximum S_M and S_A, and the point at which Tracking Rate begins to increase sharply.

(iii) OBC's determined in the above manner were found to be on average, 1.0% greater than those determined for nominally identical mixtures using the Marshall method.

7.6 Relationship between Marshall Results and Wheel Tracking Results

(i) Both Marshall Stability and Marshall Quotient are strongly related to deformation, as measured in the Wheel-Tracking test.

(ii) For H.R.A. mixtures containing between 30 and 55% by mass stone, the following relationships were derived:

$$\underset{\text{(mm/hr)}}{\text{Tracking rate}} = 125\underset{\text{(kN)}}{(\text{Marshall Stability})}^{-2.1}$$

$$\underset{\text{(mm/hr)}}{\text{Tracking rate}} = 3.4\underset{\text{(kN/mm)}}{(\text{Marshall Quotient})}^{-1.3}$$

$$\underset{\text{(mm)}}{RD_{1000}} = 64\underset{\text{(kN)}}{(\text{Marshall Stability})}^{-1.5}$$

$$\underset{\text{(mm)}}{RD_{1000}} = 4.6\underset{\text{(kN/mm)}}{(\text{Marshall Quotient})}^{-0.8}$$

(iii) All of the above relationships were found to be independent of the type of sand used in the mix, except in the case of that between RD_{1000} and Marshall Quotient, for which a separate relationship was found to exist for each of the two sands studied.

7.7 Optimum Binder Content in Relation to Mixture Properties

(i) For H.R.A. mixtures containing between 30 and 55% by mass of stone, the binder content corresponding to the point at which Tracking Rate (as determined by the Wheel Tracking test) begins to rise sharply coincides with the binder content at which the aggregate structure achieves its densest packing (under the conditions of Roller compaction).

(ii) For H.R.A. mixtures containing between 0 and 55% by mass of stone, the binder content corresponding to maximum Marshall Stability, coincides approximately with the binder content at which the aggregate structure achieves its densest packing (under conditions of Marshall Compaction).

(iii) The OBC's determined from the results obtained in Marshall and Wheel-Tracking tests, are only slightly greater than the binder content at which the aggregate structure attains its densest packing (under conditions of Marshall and Roller Compaction respectively).

7.8 Mixture Properties in Relation to Resistance to Deformation

(i) The relationships between Marshall Parameters and Tracking Rate indicate that for H.R.A. mixtures containing between 30 and 55% by mass stone, Tracking Rate begins to increase sharply for values of Marshall Stability and Marshall Quotient below 7.0 kN and 1.5 kN/mm, respectively.

(ii) In a similar manner to the above, it was found that little advantage (in terms of resistance to deformation) is gained from the use of mixtures having exceptionally high values of Marshall Stability or Quotient.

(iii) It is suggested that on the basis of the relationships established during the current investigation and the recommended maximum Wheel-Tracking rates for given volumes; Stone-Filled H.R.A. mixtures carrying 6000 commercial vehicles per lane per day in the U.K., would be required to possess the following properties.

Marshall Stability = 7.5 kN)
) minimum
Marshall Quotient = 1.5 kN/mm)

(iv) For a 1 in 20 chance that the material falls outside specification, these minimum values of Marshall Stability and Quotient, are necessarily increased to 9.4 kN and 2.0 kN/mm respectively.

7.9 Principal Findings and Conclusions

The author considers all three test methods (Marshall, Indirect-Tensile and Wheel-Tracking) to be suitable for applications to Mix Design. For the H.R.A. mixtures considered, the parameters measured in each (Marshall Stability, Indirect-Tensile Strength and Wheel-Tracking Rate) were found to be capable of detecting changes in binder content, stone content and type of fine aggregate. Further, when applied to H.R.A. mixtures, over a range of binder content, the results obtained were able to indicate changes in binder requirement, as a result of changes in stone content and fine aggregate type.

The Wheel-Tracking test might at first sight be considered the best of the three, as it gives an assessment of mixture performance under "realistic" loading conditions. However, from the point of view of the time necessarily devoted to the manufacture and testing of specimens, it's use for routine purposes becomes less attractive. Utilising a system such as the Marshall test, facilitates the assessment of a large number of compositional variations within a relatively short time. (see table 54).

Table 54

Marshall Test - Wheel-Tracking Test (Testing Sequence)

(Figures in brackets - number of specimens dealt with in each operation).

	MARSHALL TEST	WHEEL-TRACKING TEST
MONDAY	Sample preparation	Sample preparation
TUESDAY	Compaction (24)	Compaction (4)
WEDNESDAY	Density-voids determination Testing (24) Sample preparation	Compaction (4)
THURSDAY	Compaction (24)	Density-Voids determination
FRIDAY	Density-voids determination Testing (24)	Testing (8)
MONDAY	Sample preparation	Sample preparation
TUESDAY	Compaction (24)	Compaction (4)
WEDNESDAY	Density-voids determination Testing (24) Sample preparation	Compaction (4)
THURSDAY	Compaction (24)	Density-voids determination
FRIDAY	Density-voids determination Testing (24)	Testing (8)

Total number of specimens tested	96	16
Number of test runs (number of binder contents shown in brackets)	4 (12)	2 (8)

The Indirect-Tensile test (conducted on Marshall specimens) has the advantage of being able to assess quickly a large number of compositional variations. However, because it provides a measure of tensile strength, the author considers its use in assessing the resistance of a mix to deformation may be limited; resistance to deformation itself being related to the mix's ability to resist the accumulation of plastic deformation. Further work is required to determine its usefulness in assessing the resistance of the mix to cracking and/or fatigue failure.

On the basis of the above, the Marshall method of Mix Design is, in the author's opinion, the best alternative at present available. However, further improvement upon the procedure at present used is considered possible. A more logical approach would be to carry out the design procedure on the Total Mix (coarse aggregate included). This would appear feasible in the light of the fact that no practical problems were experienced in extending the procedure to H.R.A. mixtures containing up to 55% by mass of stone. The OBC's determined for such mixtures (based on the mean of the binder contents corresponding to maximum S_M, S_A and S) were found in each case to coincide closely to the point at which the aggregate structure attains its densest packing. This situation of densest packing has been shown (in Wheel-Tracking tests) to correspond to a binder content, above which the mixture's resistance to deformation begins to decrease markedly. In the author's opinion, this tends to indicate that OBC's determined in the above manner, would provide a mixture having the best compromise between resistance to deformation on the one hand, and durability on the other.

However, before total confidence can be placed in results obtained, significant improvements in reproducibility must be made. On the basis of the results obtained in this investigation, the author considers this may be achieved (in part) by:-

(i) utilising a testing system which allows the continuous measurement of Force and Deformation during the test, thereby removing any "human" element from the determination of Stability and Flow

(ii) exercising closer control over the compaction and testing equipment (and procedures) to be used, i.e. the specification of only a <u>single</u> compaction and test method

(iii) the introduction of methods by which the "calibration" of the compaction and testing equipment could be checked against required standards.

The existence of a close relationship between Marshall parameters and resistance to deformation (as measured in the Wheel-Tracking test) for H.R.A. mixtures containing 30 to 55% by mass of stone, means that design criteria could be established, in order to ensure that mixtures could be designed to have the required degree of resistance to deformation for a given application.

Further, Mix Design in terms of the Total-Mix would also enable the specification of minimum and maximum void contents, to ensure that the mixtures produced possess adequate durability. More importantly however, it would enable the as-constructed density of pavements to be controlled by means of "end-point" specification, the density required in construction being specified as a percentage of the laboratory density attained under Marshall compaction.

From the point of view of resistance to deformation and durability, the degree of compaction has been shown to be of great importance in determining the amount of binder required to produce an optimum mixture composition.

In assessing the suitability of the optimum binder contents determined using the Marshall method, it is essential that they are compared with the binder contents of in-service mixtures which display optimum performance with respect to resistance to deformation. In this respect, the results of the current investigation will take on increased importance, as information regarding the performance of the 30% stone H.R.A. mixtures laid in experimental sections on the A33 Winchester by-pass, becomes available.

FURTHER WORK

The author considers that there are several topic areas, contained within the present study, which warrant further investigation as follows:-

1. An inter-laboratory study (using nominally identical mixtures) to determine if the close duplication of the apparatus and procedures used in the execution of the Marshall Test, leads to an improvement in the Reproducibility of test results (as compared to the values widely quoted at present).

2. A study (using nominally identical mixtures), to determine if different methods of measuring Marshall Stability, have a material effect upon the results obtained. (i.e. difference between Load Cell and Proving Ring).

3. Correlation of Indirect-Tensile Test results with Fatigue Life (for H.R.A. mixtures), to establish if this test method (Indirect-tensile) might be useful for assessing mixtures from this point of view.

4. A detailed study of the effect of degree of compaction (roller) upon the performance of H.R.A. mixtures in the Wheel-Tracking Test and the binder requirement (for optimum performance) of such mixtures in different states of compaction.

5. Further studies of the nature described herein, to establish further correlations between Marshall Parameters (Stability and Quotient) and Tracking Rate, in order to determine if a single relationship between these parameters for H.R.A. mixtures containing

a wide range of fine aggregate types.

6. Re-analysis of the results obtained in the current investigation when results regarding the performance of the A33 test sections become available. This will allow the laboratory OBC's to be compared with in-service OBC's and permit the determination of the compactive effort required to reproduce in-service densities in the laboratory.

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A. COMPUTER PROGRAMS

A.1 Introduction

The computer programs used for the calculation of mixture proportions and the analysis of the experimental data, are presented in the following sections.

Sample printouts are presented, to which the reader is referred in order to obtain details of the calculations involved. A brief summary of each program is given at the start of each section.

N.B. All programs are written in Fortan IV and were run on an IBM 370 machine.

A.2 MIX : Mixture Composition

Calculates the masses (and % by mass) of coarse aggregate, fine aggregate, filler and binder required to produce a specimen having a given Total Mass, Stone Content and binder content. Such that the ratio of material passing a 2.36 mm sieve and retained on a 75 micron sieve, to material passing a 75 micron sieve, is 6:1.

```
/LOAD FORTG1
C PROGRAM TO PROPORTION MIXES FOR MARSHALL TEST
C EACH MIX TO HAVE 6 TO 1 RATIO OF MATERIAL PASSING 2.36MM SIEVE AND
C RETIANED ON 75 MIC SIEVE TO MATERIAL PASSING 75 MIC SIEVE
C DEFINE ALL VARIABLES AS BEING REAL
      REAL ST,B,S,F,WST,WB,WS,WF,WM,SF,WSF,K,Y,Z,CR,FR
      INTEGER J,N
C FIRST READ IS EXECUTED ONLY ONCE TO READ FIRST DATA CARD
C READ CONSTANT PARAMETERS
C WM=TOTAL WT OF MIX
C K =REQUIRED PERCENTAGE RETAINED ON 75 MIC SIEVE TO GIVE 6 TO 1 RATIO
C CR=PERCENTAGE OF SAND RETIANED ON 75 MIC SIEVE
C FR=PERCENTAGE OF FILLER RETAINED ON 75 MIC SIEVE
C ST=PERCENT BY WT OF STONE IN MIX
C N =NO OF DATA CARDS OR LINES OF DATA
    1 READ(9,2) WM,K,CR,FR,ST,N
    2 FORMAT(2F6.0,3F5.0,I3)
C SECOND READ IS EXECUTED FOR EVERY DATA CARD AFTER THE FIRST
C READ PERCENT BY WT OF BINDER REQUIRED IN MIX (B)
      J=1
    3 READ(9,4) B
    4 FORMAT(F4.0)
      J=J+1
C CALCULATE WT OF BINDER REQUIRED IN MIX (WB)
    5 WB=WM*(B/100)
C CALCULATE PERCENT BY WT OF SAND+FILLER IN MIX (SF)
    6 IF(ST.EQ.0.0) GO TO 8
    7 IF(ST.NE.0.0) GO TO 10
    8 SF=100-B
    9 GO TO 11
   10 SF=(100-ST)-B
C CALCULATE WT OF SAND+FILLER IN MIX (WSF)
   11 WSF=WM*(SF/100)
C CALCULATE PERCENTAGE OF SAND REQUIRED IN MIX (Y)
   12 Y=(K-FR)/(CR-FR)
C CALCULATE PERCENTAGE OF FILLER REQUIRED IN MIX (Z)
   13 Z=1-Y
C CALCULATE WT OF SAND REQUIRED IN MIX (WS)
   14 WS=WSF*Y
C CALCULATE WT OF FILLER REQUIRED IN MIX (WF)
   15 WF=WSF*Z
C CALCULATE WT OF STONE REQUIRED IN MIX (WST)
  100 IF(ST.EQ.0.0) GO TO 101
  200 IF(ST.NE.0.0) GO TO 16
  101 WST=0.00
  102 GO TO 17
   16 WST=WM*(ST/100)
C CALCULATE PERCENT OF TOTAL MIX TAKEN UP BY SAND (S)
   17 S=(WS/WM)*100
C CALCULATE PERCENT OF TOTAL MIX TAKEN UP BY FILLER (F)
   18 F=(WF/WM)*100
C WRITE VALUES OF ST,S,F,B,WST,WS,WF,WB
   19 WRITE(6,20) ST,S,F,B,WST,WS,WF,WB
   20 FORMAT(23H     STONE (PERCENT) = F6.2/23H     SAND   (PERCENT) = F6
     1.2/23H     FILLER (PERCENT) = F6.2/23H     BINDER (PERCENT) = F6.2//
     223H     STONE    (GRAMS) = F6.1/23H     SAND  -  (GRAMS) = F6.1/23H
     3    FILLER   (GRAMS) = F6.1/23H     BINDER   (GRAMS) = F6.1////)
   21 IF(J.NE.N) GO TO 3
      END
/DATA
```

```
 EXECUTION BEGINS       3.53
 ?
 1000.0 35.71 39.5 12.0 30.0
 ?
  6.0
     STONE  (PERCENT) =  30.00
     SAND   (PERCENT) =  55.17
     FILLER (PERCENT) =   8.83
     BINDER (PERCENT) =   6.00

     STONE    (GRAMS) =  300.0
     SAND     (GRAMS) =  551.7
     FILLER   (GRAMS) =   88.3
     BINDER   (GRAMS) =   60.0
```

A.3 MARSH : Marshall Test Results

Analyses of the results obtained in the Marshall Test. Calculates the Density and Void Content of each specimen, and the values of Stability, Flow and Quotient for each specimen.

```
/LOAD FORT31
C PROGRAM TO ANALYSE RESULTS OF MARSHALL TESTS
C DEFINE ALL VARIABLES AS BEING REAL
      REAL W,WW,W1,W2,W3,WB,S1,S2,S3,SB,S,F,SD,FD,B,SM,SA,STM,VM,VA,VF,
     1SR,FR,SC,Q,CF,WS,WF,WM,SF,WSF,X,Y,Z,CR,RF
      INTEGER J,N
C THE FIRST READ IS EXECUTED ONLY ONCE TO READ CONSTANT PARAMETERS
C NOW READ CONSTANT PARAMETERS
C S1=RELATIVE DENSITY OF STONE
C S2=RELATIVE DENSITY OF SAND
C S3=RELATIVE DENSITY OF FILLER
C SB=RELATIVE DENSITY OF BITUMEN
C FD=CONVERSION FACTOR FOR FLOW
C SD=CONVERSION FACTOR FOR STABILITY
C N =NO OF DATA CARDS OR LINES OF DATA
C WM=TOTAL WT OF MIX
C W1=PERCENT BY WT STONE IN MIX
C X =PERCENT REQUIRED RETAINED ON 75 MIC SIEVE TO GIVE 6 TO 1 RATIO
C CR=PERCENT SAND RETAINED ON 75 MIC
C RF=PERCENT FILLER RETAINED ON 75 MIC
    2 READ(9,3) S1,S2,S3,SB,FD,SD,N,WM,X,W1,CR,RF
    3 FORMAT(4F5.0,2F6.0,I3,F7.0,F6.0,3F5.0)
C WRITE AND LABEL CONSTANT PARAMETERS JUST READ
      J=1
    4 WRITE(6,5) S1,S2,S3,SB,FD,SD
    5 FORMAT(1H1,31HCONSTANT PARAMETERS IN ANALYSIS//
     11H ,30HRELATIVE DENSITY OF STONE    = F4.2 //
     21H ,30HRELATIVE DENSITY OF SAND     = F4.2 //
     31H ,30HRELATIVE DENSITY OF FILLER   = F4.2 //
     41H ,30HRELATIVE DENSITY OF BITUMEN = F4.2 //
     51H ,30HFLOW CONVERSION FACTOR      = F5.3//
     61H ,30HSTABILITY CONVERSION FACTOR = F5.1 //)
C GIVE HEADING AND LABEL TABLE OF CALCULATED VALUES
  200 WRITE(6,100)
  100 FORMAT(1H ,53HANALYSIS OF MARSHALL TEST,TABULATION OF CALCULATED
     1VALUES //
     21H ,69H WB      B      SM     SA    STH     VM     VA     VF     SR     SC
     3  FR     Q  //)
C NEXT READ WILL BE EXECUTED FOR EVERY DATA CARD AFTER THE FIRST
    6 READ(9,7) W,WW,WB,S,F
C WHERE
C W =WT OF SPEC IN AIR
C WW=WT OF SPEC IN WATER
C WB=PERCENT BY WT OF BITUMEN IN MIX
C S =DIST ON RECORDER REPRESENTING MAX LOAD
C F =DIST ON RECORDER REPRESENTING FLOW AT MAX LOAD
    7 FORMAT(2F6.0,2F5.0,F6.0)
      J=J+1
C NEXT STATEMENTS CALC W2 AND W3 TO GIVE 6 TO 1 RATIO
C W2=PERCENT BY WT SAND IN MIX
C W3=PERCENT BY WT FILLER IN MIX
   70 IF(W1.EQ.0.0) GO TO 72
   71 IF(W1.NE.0.0) GO TO 74
C CALC PERCENT SAND + FILLER IN MIX (SF)
   72 SF=100-WB
   73 GO TO 75
   74 SF=(100-W1)-WB
C CALC WT SAND + FILLER IN MIX (WSF)
   75 WSF=WM*(SF/100)
C CALC PERCENT SAND REQUIRED IN WSF (Y)
   76 Y=(X-RF)/(CR-RF)
C CALC PERCENT FILLER REQUIRED IN WSF (Z)
   77 Z=1-Y
```

```
C CALC WT SAND REQUIRED IN MIX (WS)
   73 WS=WSF*Y
C CALC WT FILLER REQUIRED IN MIX (WF)
   79 WF=WSF*Z
C CALC PERCENT SAND IN TOTAL MIX (W2)
   30 W2=(WS/WM)*100
C CALC PERCENT FILLER IN TOTAL MIX (W3)
   31 W3=(WF/WM)*100
C BEGIN CALCULATIONS
C B=VOLUME OF SPECIMEN
    8 B=W-WW
C SM=RELATIVE DENSITY OF SPECIMEN
    9 SM=W/B
C SA=COMPACTED AGGREGATE DENSITY
   10 SA=SM*((100-WB)/100)
  300 IF(W1.EQ.0.0) GO TO 400
  301 IF(W1.NE.0.0) GO TO 11
C STH=THEORETICAL MAX RELATIVE DENSITY
  400 STH=100/((W2/S2)+(W3/S3)+(WB/SB))
  401 GO TO 12
   11 STH=100/((W1/S1)+(W2/S2)+(W3/S3)+(WB/SB))
C VM=VOIDS IN MIX
   12 VM=((STH-SM)/STH)*100
C VA=VOIDS IN MINERAL AGGREGATE
   13 VA=VM+((WB*SM)/SB)
C VF=VOIDS FILLED WITH BITUMEN
   14 VF=((WB*SM)/(VA*SB))*100
C OBTAIN ACTUAL FLOW VALUE IN MM,(FR),BYMULTIPLYING THE DIST
C REPRESENTING FLOW ON THE RECORDER(F) BY CONVERSION FACTOR(FD)
   15 FR=FD*F
C OBTAIN ACTUAL STABILITY VALUE IN NEWTONS(SR) BY MULTIPLYING DIST
C REPRESENTING STABILITY ON RECORDER(S) BY CONVERSION FACTOR(SD)
   16 SR=SD*S
C DEPENDING UPON SPECIMEN VOLUME(B) A CORRECTION FACTOR HAS TO BE
C APPLIED TO STABILITY (SR),CORRECTION FACTOR (CF) IS
C OBTAINED BY EXTRAPOLATING TABLE 12 OF B.S.594
   17 CF=2.5-(0.0029126*B)
C CALCULATE CORRECTED STABILITY (SC)
   18 SC=SR*CF
C Q=MARSHALL QUOTIENT=STABILITY/FLOW
C DIVIDING SC BY 1000 GIVES Q IN KN/MM
   43 Q=(SC/1000)/FR
C WRITE ALL CALCULATED VALUES ALONG WITH BINDER CONTENT(WB) FOR REF
   44 WRITE(6,45) WB,B,SM,SA,STH,VM,VA,VF,SR,SC,FR,Q
   45 FORMAT(1H ,F4.1,F7.1,3F6.3,3F6.2,2F6.0,2F6.2)
   46 IF(J.NE.N) GO TO 6
      END
/DATA
```

```
EXECUTION BEGINS     4.9S
?
 0.00 2.62 2.70 1.03 0.847 124.5 13 1130.0 35.71  0.0 97.5 12.0

CONSTANT PARAMETERS IN ANALYSIS

RELATIVE DENSITY OF STONE    = 0.0

RELATIVE DENSITY OF SAND     = 2.62

RELATIVE DENSITY OF FILLER   = 2.70

RELATIVE DENSITY OF BITUMEN  = 1.03

FLOW CONVERSION FACTOR       = 0.847

STABILITY CONVERSION FACTOR  = 124.5


ANALYSIS OF MARSHALL TEST,TABULATION OF CALCULATED  VALUES

 WB     B      SM     SA    STH     VM     VA     VF     SR     SC     FR     Q


?
1090.5 568.5 12.0 47.9  7.77
12.0  522.0 2.089 1.838 2.217  5.78 30.12 80.81 5964. 5842.  6.58  0.89
?
1088.1 569.3 12.0 48.6  7.75
12.0  518.8 2.097 1.846 2.217  5.41 29.84 81.88 6051. 5984.  6.56  0.91
?
1091.8 572.4 12.0 46.3  7.98
12.0  519.4 2.102 1.850 2.217  5.20 29.69 82.50 5764. 5691.  6.76  0.84
?
1088.8 569.1 12.0 45.3  8.09
12.0  519.7 2.095 1.844 2.217  5.51 29.92 81.58 5640. 5563.  6.85  0.81
?
1087.6 569.3 12.0 43.2  7.45
12.0  518.3 2.098 1.847 2.217  5.36 29.81 82.02 5378. 5327.  6.31  0.84
```

A.4 SPLIT : Indirect-Tensile Test Results

Analyses of the results obtained in the Indirect-Tensile Test. Calculates the Density and Void Content of each specimen, and the values of Indirect-Tensile Strength, Vertical deformation at Failure and Tensile Quotient, for each specimen.

```
/LOAD FORT31
C PROGRAM TO ANALYSE RESULTS OF SPLITTING TESTS
C DEFINE ALL VARIABLES AS BEING REAL
      REAL W,WW,W1,W2,W3,WB,S1,S2,S3,SB,S,F,SD,FD,B,SM,SA,STH,WM,VA,VF,
     1SR,VD,TS,TC,VS,CF,WS,WF,VM,SF,WSF,X,Y,Z,CR,RF,H
      INTEGER J,N
C THE FIRST READ IS EXECUTED ONLY ONCE TO READ CONSTANT PARAMETERS
C NOW READ CONSTANT PARAMETERS
C S1=RELATIVE DENSITY OF STONE
C S2=RELATIVE DENSITY OF SAND
C S3=RELATIVE DENSITY OF FILLER
C SB=RELATIVE DENSITY OF BITUMEN
C FD=CONVERSION FACTOR FOR DEFN
C SD=CONVERSION FACTOR FOR VERT LOAD
C N =NO OF DATA CARDS OR LINES OF DATA
C WM=TOTAL WT OF MIX
C W1=PERCENT BY WT STONE IN MIX
C X =PERCENT REQUIRED RETAINED ON 75 MIC SIEVE TO GIVE 6 TO 1 RATIO
C CR=PERCENT SAND RETAINED ON 75 MIC
C RF=PERCENT FILLER RETAINED ON 75 MIC
    2 READ(9,3) S1,S2,S3,SB,FD,SD,N,WM,X,W1,CR,RF
    3 FORMAT(4F5.0,2F6.0,I3,F7.0,F6.0,3F5.0)
C WRITE AND LABEL CONSTANT PARAMETERS JUST READ
      J=1
    4 WRITE(6,5) S1,S2,S3,SB,FD,SD
    5 FORMAT(1H1,31HCONSTANT PARAMETERS IN ANALYSIS//
     11H ,30HRELATIVE DENSITY OF STONE    = F4.2 //
     21H ,30HRELATIVE DENSITY OF SAND     = F4.2 //
     31H ,30HRELATIVE DENSITY OF FILLER   = F4.2 //
     41H ,30HRELATIVE DENSITY OF BITUMEN  = F4.2 //
     51H ,30HDEFN CONVERSION FACTOR       = F5.3//
     61H ,30HVERT LOAD CONVERSION FACTOR = F5.1 //)
C GIVE HEADING AND LABEL TABLE OF CALCULATED VALUES
  200 WRITE(6,100)
  100 FORMAT(1H ,53HANALYSIS OF SPLITTING TEST,TABULATION OF CALCULATED
     1VALUES //
     21H ,69H WB    B     SM     SA    STH    WM     VA     VF     TS     TC
     3  VD     VS  //)
C NEXT READ WILL BE EXECUTED FOR EVERY DATA CARD AFTER THE FIRST
    6 READ(9,7) W,WW,H,WB,S,F
C WHERE
C W =WT OF SPEC IN AIR
C WW=WT OF SPEC IN WATER
C H =SPECIMEN HT
C WB=PERCENT BY WT OF BITUMEN IN MIX
C S =DIST ON RECORDER REPRESENTING MAX LOAD
C F =DIST ON RECORDER REPRESENTING FLOW AT MAX LOAD
    7 FORMAT(3F6.0,2F5.0,F6.0)
      J=J+1
C NEXT STATEMENTS CALC W2 AND W3 TO GIVE 6 TO 1 RATIO
C W2=PERCENT BY WT SAND IN MIX
C W3=PERCENT BY WT FILLER IN MIX
   70 IF(W1.EQ.0.0) GO TO 72
   71 IF(W1.NE.0.0) GO TO 74
C CALC PERCENT SAND + FILLER IN MIX (SF)
   72 SF=100-WB
   73 GO TO 75
   74 SF=(100-W1)-WB
C CALC WT SAND + FILLER IN MIX (WSF)
   75 WSF=WM*(SF/100)
C CALC PERCENT SAND REQUIRED IN WSF (Y)
   76 Y=(X-RF)/(CR-RF)
C CALC PERCENT FILLER REQUIRED IN WSF (Z)
   77 Z=1-Y
```

```
C CALC WT SAND REQUIRED IN MIX (WS)
  73 WS=WSF*Y
C CALC WT FILLER REQUIRED IN MIX (WF)
  79 WF=WSF*Z
C CALC PERCENT SAND IN TOTAL MIX (W2)
  30 W2=(WS/WM)*100
C CALC PERCENT FILLER IN TOTAL MIX (W3)
  31 W3=(WF/WM)*100
C BEGIN CALCULATIONS
C B=VOLUME OF SPECIMEN
   3 B=W-WW
C SM=RELATIVE DENSITY OF SPECIMEN
   9 SM=W/B
C SA=COMPACTED AGGREGATE DENSITY
  10 SA=SM*((100-WB)/100)
 300 IF(W1.EQ.0.0) GO TO 400
 301 IF(W1.NE.0.0) GO TO 11
C STH=THEORETICAL MAX RELATIVE DENSITY
 400 STH=100/((W2/S2)+(W3/S3)+(WB/SB))
 401 GO TO 12
  11 STH=100/((W1/S1)+(W2/S2)+(W3/S3)+(WB/SB))
C VM=VOIDS IN MIX
  12 VM=((STH-SM)/STH)*100
C VA=VOIDS IN MINERAL AGGREGATE
  13 VA=VM+((WB*SM)/SB)
C VF=VOIDS FILLED WITH BITUMEN
  14 VF=((WB*SM)/(VA*SB))*100
C OBTAIN ACTUAL DEFN VALUE IN MM,(VD),BYMULTIPLYING THE DIST
C REPRESENTING DEFN ON THE RECORDER(F) BY CONVERSION FACTOR(FD)
  15 VD=FD*F
C OBTAIN ACTUAL VERT LOAD VALUE IN NEWTONS(SR) BY MULTIPLYING DIST
C REPRESENTING VERT LOAD ON RECORDER(S) BY CONVERSION FACTOR(SD)
  16 SR=SD*S
C CALC TENSILE STRENGHT (TS) IN KN/SQMM
  17 TS=(2*SR/1000)/(3.142*101.6*H)
C CALC TENSILE COEFF UNDER DIAMETRAL COMPRESSION (TC)
  18 TC=SR/(H*VD)
C CALC VERT DIAMETRAL STRAIN (VS)
  19 VS=VD/101.6
C WRITE ALL CALCULATED VALUES ALONG WITH BINDER CONTENT(WB) FOR REF
  44 WRITE(6,45) WB,B,SM,SA,STH,VM,VA,VF,TS,TC,VD,VS
  45 FORMAT(1H ,F4.1,F7.1,3F6.3,3F6.2,2F6.1,F6.2,F6.3)
  46 IF(J.NE.N) GO TO 6
     END
/DATA
EXECUTION BEGINS     5.0S
?
 0.00 2.62 2.70 1.03 0.347 124.5 19 1100.0 35.71  0.0 97.5 12.0

CONSTANT PARAMETERS IN ANALYSIS

RELATIVE DENSITY OF STONE    = 0.0

RELATIVE DENSITY OF SAND     = 2.62

RELATIVE DENSITY OF FILLER   = 2.70

RELATIVE DENSITY OF BITUMEN  = 1.03

DEFN CONVERSION FACTOR       = 0.347

VERT LOAD CONVERSION FACTOR  = 124.5


ANALYSIS OF SPLITTING TEST,TABULATION OF CALCULATED VALUES

 WB    B      SM    SA   STH    VM    VA    VF    TS    TC    VD    VS


?
1031.2 549.7 67.00  9.5 55.3  7.72
 9.5  531.5 2.034 1.341 2.292 11.26 30.02 62.50 0.650 15.36  6.54
?
1034.5 551.9 67.00  9.5 55.3  6.23
 9.5  532.6 2.036 1.343 2.292 11.17 29.95 62.70 0.644 19.32  5.32
?
1090.3 560.5 65.75 10.0 57.4  7.76
10.0  530.3 2.057 1.351 2.277  9.66 29.63 67.40 0.631 16.54  6.57
?
1083.7 557.5 66.75 10.0 58.1  6.96
10.0  526.2 2.059 1.354 2.277  9.55 29.54 67.63 0.679 13.33  5.90
?
1093.3 571.0 65.50 10.5 59.1  7.56
10.5  527.3 2.033 1.364 2.262  7.91 29.14 72.37 0.704 17.54  6.40
?
1092.3 564.3 66.00 10.5 60.3  7.61
10.5  528.0 2.070 1.352 2.262  8.49 29.59 71.31 0.713 17.65  6.45
```

B. DETAILED TEST METHODS

B.1 The Marshall Test:

B.1.1 Preparation of Constituent Materials:

1. Keep aggregates from different sources separate and dry in an oven at 150°C overnight.
2. Thoroughly blend each aggregate by riffling to ensure representative sampling.
3. Weigh out into suitable containers, the required masses of each aggregate (to the nearest 1 gram). Place sufficient in each tin to produce a single specimen of the required size.
4. Label each container with the appropriate specimen identification number.
5. Heat the binder in bulk until sufficiently fluid to stir, decant into small tins, sufficient in each for a single specimen, cover and allow to cool.

B.1.2 Preparation Prior to Manufacture:

1. Place aggregate containers, mixing bowls and whisk in an oven maintained at 165°C and leave overnight.
2. Place tins of binder in an oven, set timing device to switch on oven, such that the binder will attain a temperature of 160°C just prior to mixing.
3. Assemble and lightly oil the compaction moulds, extension collars and baseplates. Place along with compactor foot and funnel, in an oven maintained at 150°C and leave overnight.
4. Prepare non-absorbent paper discs, spatulas, thermometer, water bucket, etc.

B.1.3 Mixing:

1. Remove mixing bowl from oven, place in hotplate and charge with the contents of a single aggregate container.
2. Mix aggregate with a spatula and form a crater at the centre.
3. Transfer bowl and contents to balance pan and tare so that the pointer just registers on the scale.
4. Remove a tin of binder from oven, remove lid, stir and pour the required amount of binder, to the nearest 0.5 gram, into the mixing bowl.
5. Mount bowl on mixer, remove whisk from oven, position and commence mixing.
6. After 60 seconds, stop mixing, clean and return whisk to oven, transfer bowl and contents to hotplate, and give a final mix using a spatula to ensure all material is thoroughly mixed in.

B.1.4 Compaction:

1. Remove mould assembly from oven, place on compaction pedestal and insert a non-absorbent paper disc.
2. Remove funnel from oven and insert in top of mould assembly.
3. Tip the contents of the mixing bowl into the mould assembly via the funnel. Clean bowl and funnel and return to oven.
4. Spade the mixture 15 times around the perimeter, 10 times at the centre to form into a dome.
5. Determine and record the temperature of the mixed material.
6. Place a second paper disc on top of the mixed material and locate mould assembly in position on compaction pedestal.
7. Remove compactor foot from oven and locate on hammer shaft. Lower foot onto the top of the material in the mould and

apply 50 blows of the compaction hammer.

8. Remove extension collar, invert mould on the baseplate and replace extension collar.

   N.B. Ensure any material which has forced its way up between the compactor foot and the side of the mould is removed, prior to inverting the mould.

9. Relocate the mould assembly on the compaction pedestal and apply a further 50 blows of the compaction hammer.

10. Dismantle mould assembly, clean and return extension collar and baseplate to oven, and place mould containing specimen in a bucket of water for approximately 15 minutes.

    N.B. For specimens with high binder contents, the baseplate should be left in position and placed in the water for about 30 minutes.

11. Extrude specimen from mould using extraction frame and jack. Clean and return mould to oven.

12. Dry specimen with a cloth, remove any burrs and place on absorbent paper on a flat bench. Mark with the appropriate specimen identification number.

13. Repeat mixing and compaction operations until all specimens have been made.

B.1.5 <u>Determination of Specimen Density - Voids</u>:

1. Determine the mass of each specimen in air, to the nearest 0.1 gram.

2. Determine the mass of each specimen completely immersed in water at 20 ± 1°C, to the nearest 0.1 gram.

   N.B. These determinations are made prior to preparing the specimens for testing, the values obtained are recorded and the calculations carried out at a later time.

B.1.6 Determination of Stability and Flow:

1. Totally immerse specimens in a waterbath maintained at 60 ± 0.5°C, for 45 minutes prior to testing.

2. Whilst specimens attain test temperature, set up and calibrate the recording equipment:

   (i) Wire up equipment as in figure B.1.1, and connect mains power supply.

   (ii) Switch on Load Cell Power Supply (L.C.P.S.), Chart Recorder and Digital Voltmeter (D.V.M.) Set the latter to read V d.c.

   (iii) Switch L.C.P.S. to "SET" position, adjust "SET 30 mv" knob until "30.00" registers on D.V.M.

   (iv) Switch L.C.P.S. to "LOAD" position, and "ATTENUATOR" on Chart Recorder to 20 mv position.

   (v) Adjust "ZERO" knob on L.C.P.S. so that pen on recorder moves across the chart away from zero line. Continue until a reading of "24.00" is obtained on the D.V.M.

   (vi) Use "VERNIER" adjustment on Chart Recorder to centre pen on the 10 inch line of the chart.

   (vii) Adjust "ZERO" knob on L.C.P.S. so that pen moves across the chart towards the zero line of the chart, until a reading of "0.00" is obtained on the D.V.M.

   (viii) Use "ZERO" adjustment on Chart Recorder

Marshall Test Recording System

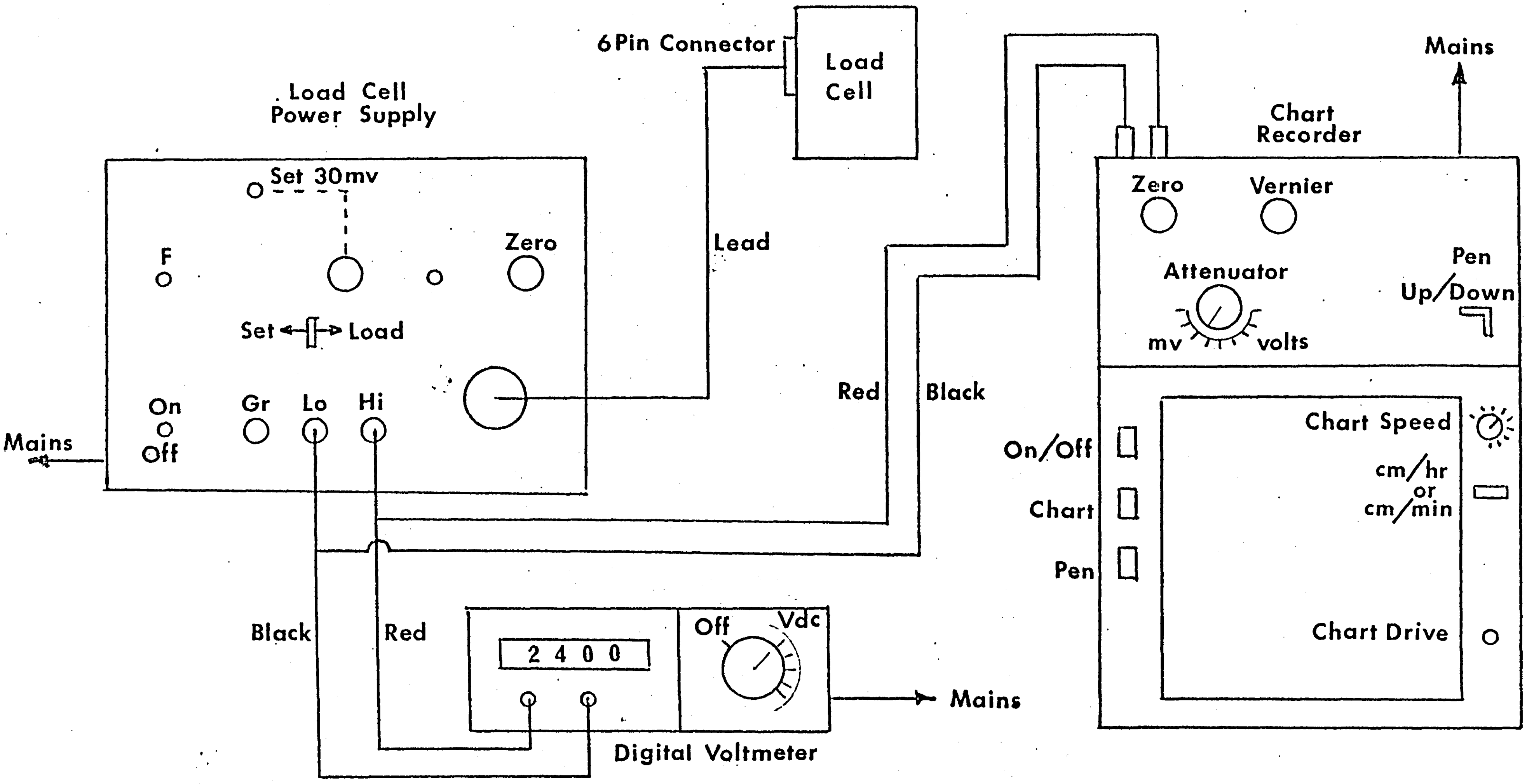


Fig.

to centre pen on zero-line of chart.

(ix) Repeat operations (v), (vi), (vii) and (viii) until no further adjustment is required, i.e. the pen is centred on the zero line and 10 inch line of the chart when D.V.M. readings are "0.00" and "24.00" mv respectively.

(x) The system is now calibrated for a Full Scale Deflection (f.s.d.) = 50 kN.

For a f.s.d. = 25 kN, set "ATTUATOR" on Chart recorder to 10 mv position.

For a f.s.d. = 12.5 kN, set "ATTUATOR" on Chart recorder to 5 mv position.

(xi) Set chart speed at 60 cm/min.

3. Remove test head from oven, where it had previously been placed to attain a temperature of 60 ± 0.5°C. Clean and lightly oil guide rods.

4. Remove specimen from waterbath, place centrally on its side in the jaws of the test head.

   N.B. Test high binder content specimens first.

5. Locate test head centrally on platern of testing machine, place ball hearing on top of test head and set up so there is a gap of approximately 4 mm between the ball bearing and load cell assembly.

6. Switch on chart, lower pen and check zero, then switch on testing machine.

7. Switch off testing machine and chart when specimen has "failed". Mark chart with approximate specimen identification number.

8. Unload specimen, remove from test head. Clean test head ready for next specimen.

9. Repeat, 4, 5, 6, 7, and 8 until all specimens have been tested, the time taken per specimen should not exceed 40 secs.

B.1.7 Flow Chart for the Marshall Test:

To assist in the development of a "duplicate" Marshall Testing Facility at E.R.C.A., a Flow Chart, indicating the sequence of operations was produced and is presented in figure B.1.2.

This relates to the determination of a Target Binder Content for H.R.A. wearing course mixtures, according to section 3, B.S. 594 (1973),(7) and goes on to include reference to Departmental Standard HD/2/79.(20)

HOT ROLLED ASPHALT
MARSHALL MIX DESIGN :

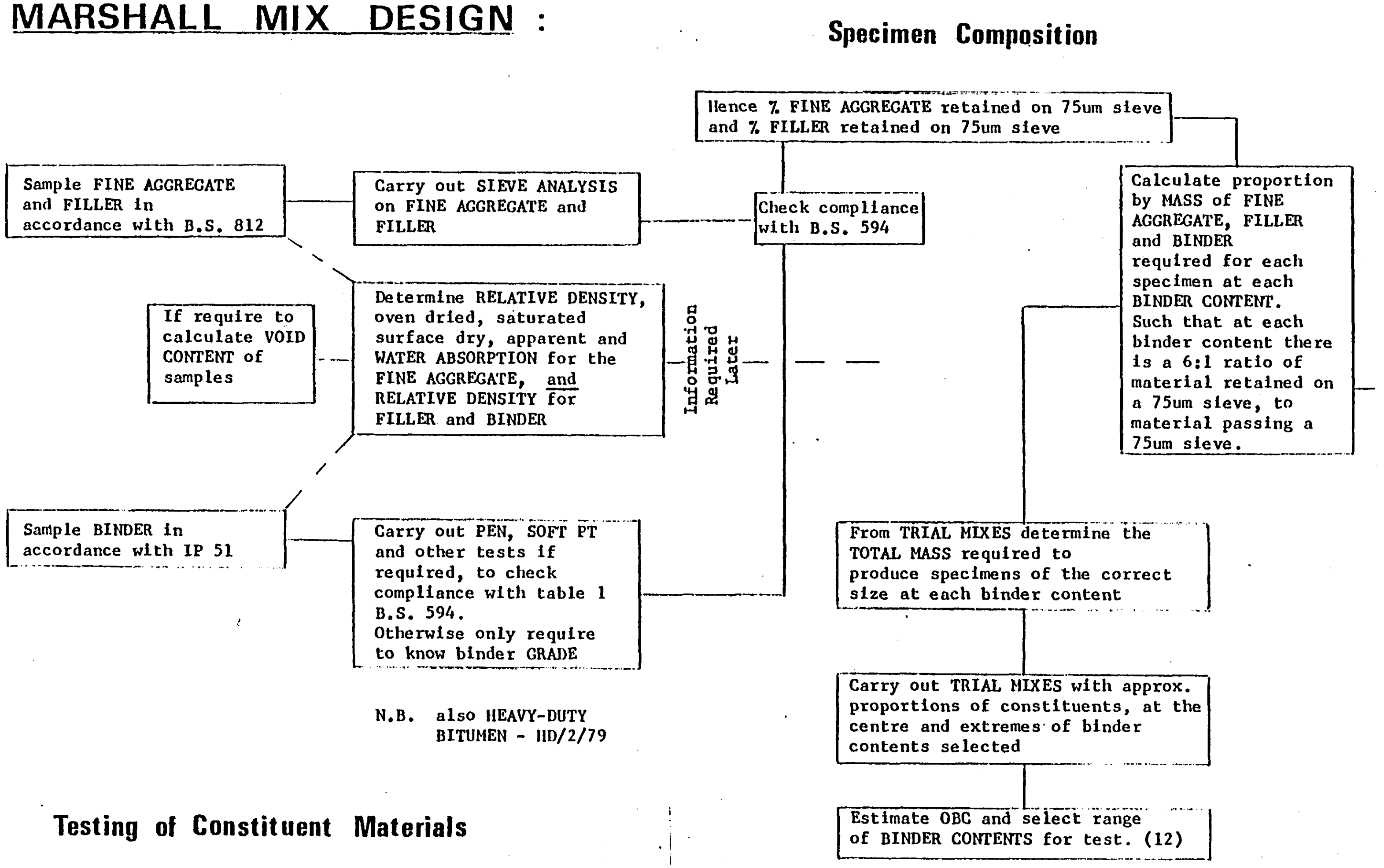
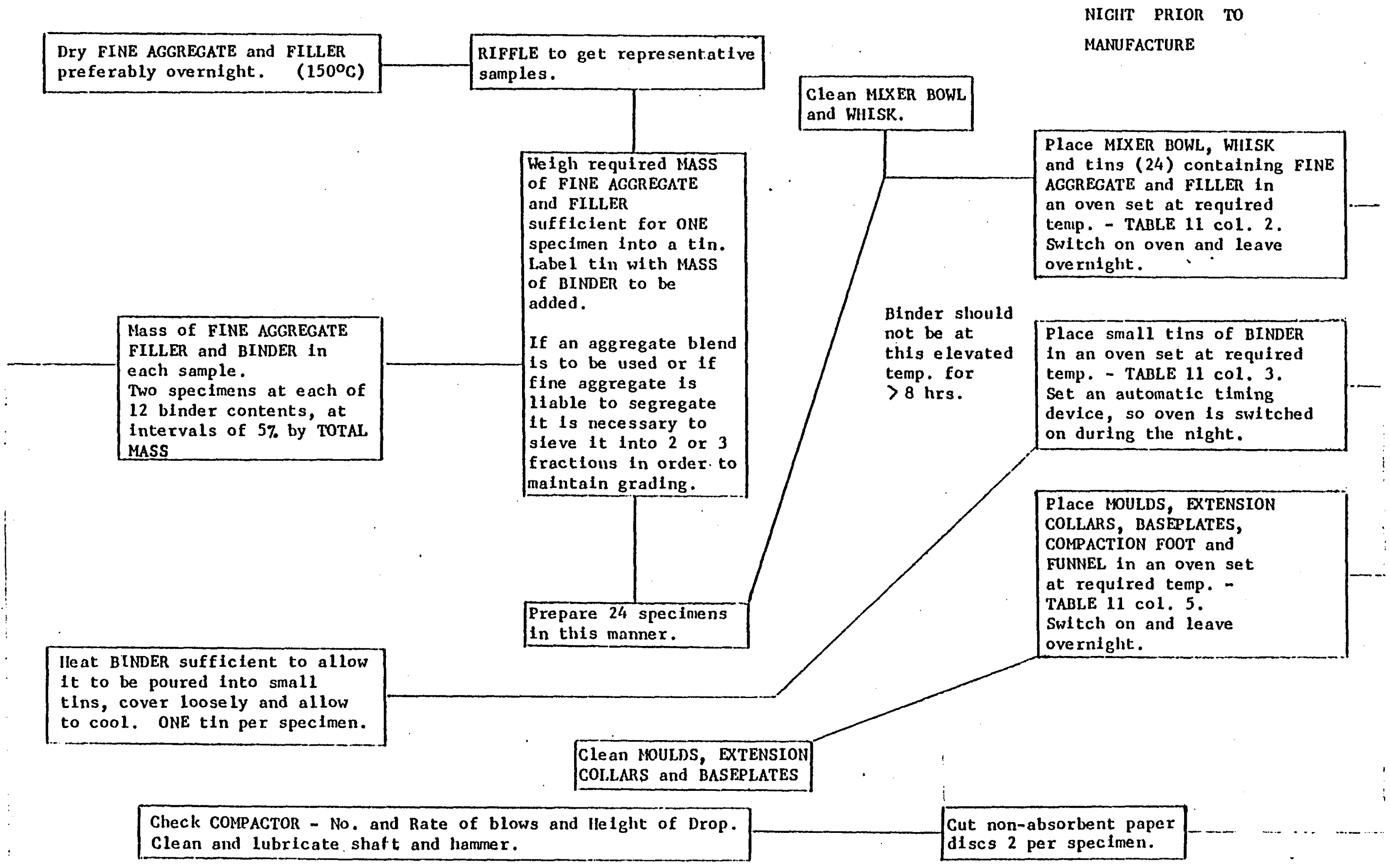


fig B.1.2

1

Preparation Prior to Manufacture



Dry FINE AGGREGATE and FILLER preferably overnight. (150°C)

RIFFLE to get representative samples.

Weigh required MASS of FINE AGGREGATE and FILLER sufficient for ONE specimen into a tin. Label tin with MASS of BINDER to be added.

If an aggregate blend is to be used or if fine aggregate is liable to segregate it is necessary to sieve it into 2 or 3 fractions in order to maintain grading.

Mass of FINE AGGREGATE FILLER and BINDER in each sample.
Two specimens at each of 12 binder contents, at intervals of 5% by TOTAL MASS

Prepare 24 specimens in this manner.

Clean MIXER BOWL and WHISK.

Place MIXER BOWL, WHISK and tins (24) containing FINE AGGREGATE and FILLER in an oven set at required temp. - TABLE 11 col. 2. Switch on oven and leave overnight.

Binder should not be at this elevated temp. for > 8 hrs.

Place small tins of BINDER in an oven set at required temp. - TABLE 11 col. 3. Set an automatic timing device, so oven is switched on during the night.

Place MOULDS, EXTENSION COLLARS, BASEPLATES, COMPACTION FOOT and FUNNEL in an oven set at required temp. - TABLE 11 col. 5. Switch on and leave overnight.

Heat BINDER sufficient to allow it to be poured into small tins, cover loosely and allow to cool. ONE tin per specimen.

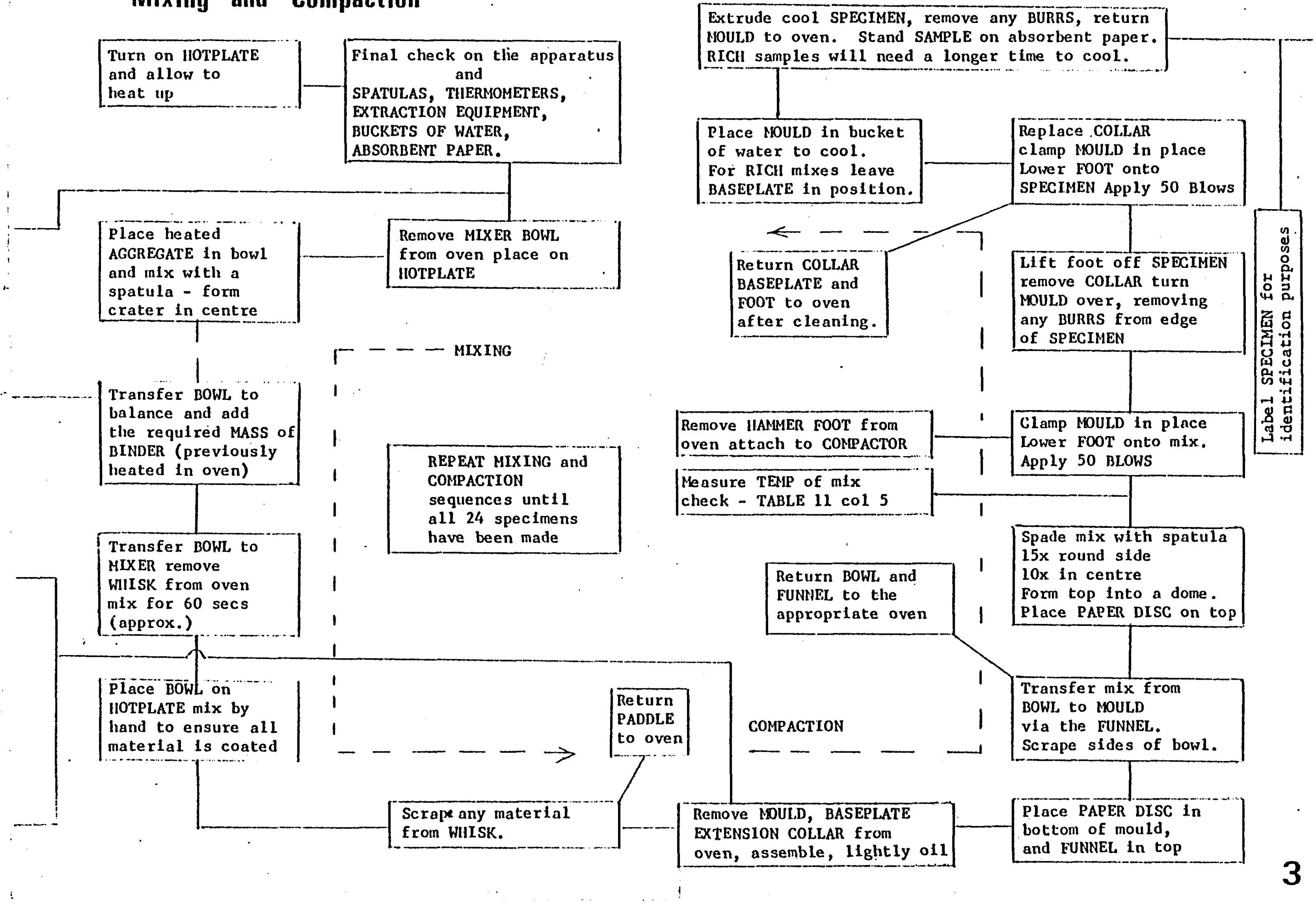
Clean MOULDS, EXTENSION COLLARS and BASEPLATES

Check COMPACTOR - No. and Rate of blows and Height of Drop. Clean and lubricate shaft and hammer.

Cut non-absorbent paper discs 2 per specimen.

2

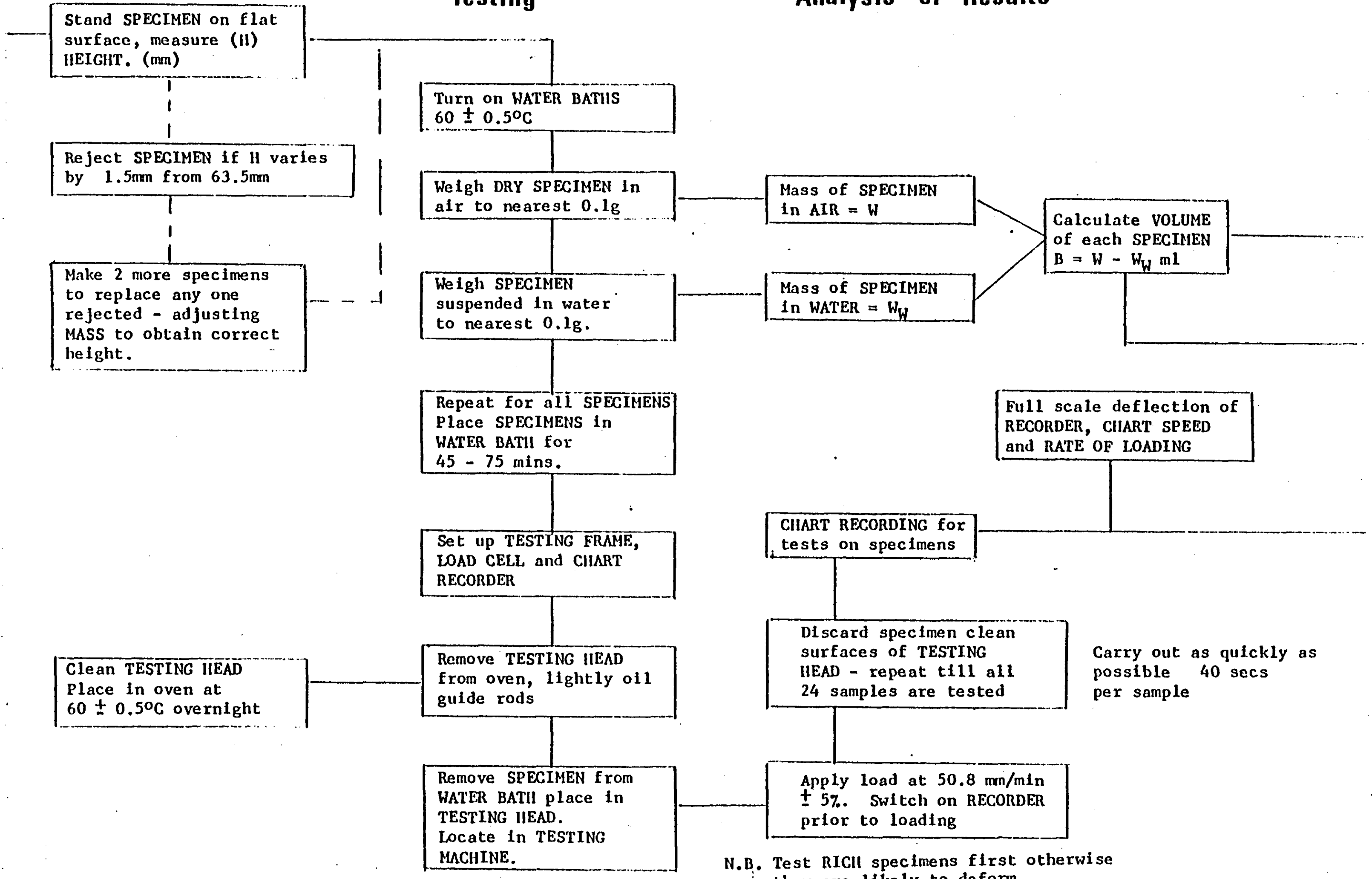
Mixing and Compaction



3

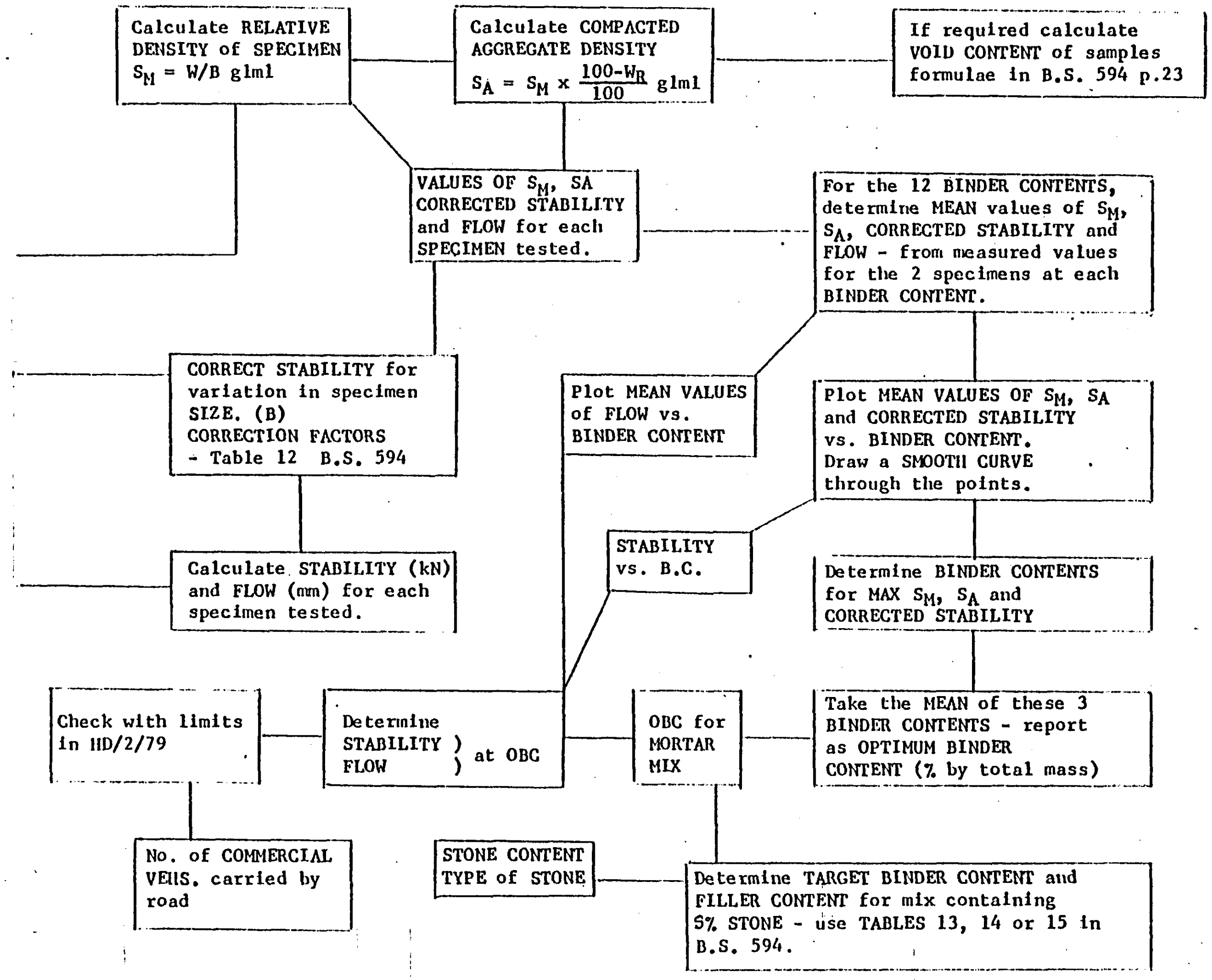
Testing

Analysis of Results



N.B. Test RICH specimens first otherwise they are likely to deform.

4



N.B. Can also calculate MARSHALL QUOTIENTS $= \frac{\text{STABILITY}}{\text{FLOW}}$ kN/mm

5

B.2 The Indirect-Tensile Test

B.2.1 Preparation of Constituent Materials

B.2.2 Preparation prior to Manufacture

B.2.3 Mixing

B.2.4 Compaction

Specimens 101.6 mm dia x 63.5 mm (approx), compacted using the automatic Marshall compactor (50 blows per face) are to be used. Hence the above operations are to be carried out in a menner identical to that described for Marshall test specimens, in sections B.1.1, 1.2, 1.3 and 1.4 respectively.

B.2.5 Determination of Specimen Height:

The average height (H) of each compacted specimen shall be determined as follows, using the apparatus described in 5.3.4.

1. Place the dial gauge assembly and baseplate on a flat, level surface.
2. Place the steel calibration block on the baseplate beneath the foot of the dial-gauge.
3. Lower the dial-gauge until a reading of approximately 1000 divs is obtained and firmly clamp it in position.
4. If necessary, adjust the position of the dial-gauge so that the reading remains constant as the steel block is moved about beneath the foot attachment. Record this initial gauge reading.
5. Place each specimen in turn on the baseplate, beneath the foot of the dial-gauge. Record the gauge reading at 5 positions on the surface of each specimen.
6. For each specimen, calculate the height at each of the 5 positions and hence determine the average height (H) to

the nearest 0.1 mm.

B.2.6 Determination of Specimen Density-Voids:

Carry out as described for the Marshall test in B.1.5.

B.2.7 Determination of Indirect-Tensile Strength:

1. Place specimens in a thermostatically controlled waterbath maintained at 25°C for at least 45 minutes.
2. Whilst specimens attain test temperature, modify the Marshall testing machine to facilitate the determination of Indirect-Tensile strength.
3. Set up and calibrate recording equipment exactly as for the Marshall test, see figure B.1.1 and section B.1.6.
4. Remove each specimen in turn from the waterbath and locate centrally between the loading strips as follows:
    - (i) position specimen centrally with respect to the scale on the lower loading strip and set up so that there is a gap of approximately 4 mm between the top of the specimen and the upper loading strip.
    - (ii) insert centering plate behind the specimen, and apply backward pressure to specimen (by hand) so that it pushes the plate into contact with the appropriate backstops.
5. Mark chart with the appropriate specimen identification number. Check zero on chart and switch on, then switch on testing machine.
6. Maintain specimen in contact with the centering plate until force is being taken by the specimen, then immediately remove the plate and allow the test to continue until the specimen fails.

7. Switch off testing machine and chart, unload specimen and discard. Repeat until all specimens have been tested.

B.3 THE WHEEL-TRACKING TEST

B.3.1 Preparation of Constituent Materials

Prepare aggregates and binder as described for the Marshall test (B.1.1), except that the aggregate for each specimen should be proportioned in two identical halves and then placed on 2 shallow trays.

B.3.2 Preparation Prior to Mixing:

1. Heat the aggregate and binder to the same temperatures and in the same manner as described for the Marshall test (B.1.2).
2. Place mixing bowl and whisk in the same oven as the aggregate and leave overnight.

N.B. The compaction mould and mould extension are not heated prior to compaction.

3. Set-up the Tracking machine for the compaction operation:
   - (i) Locate roller segment, mould, mould extension and load hanger.
   - (ii) Set position of knock-offs on table, such that the distance of travel of the mould is 305 mm.
   - (iii) Set control valves on hydraulic power pack such that the speed of travel of the mould is 25 passes per minute.

B.3.3 Mixing:

1. Remove mixing bowl from oven and charge with one tray of aggregate, mix with a spatula and form a crater at the centre.
2. Add the required mass of binder and mix in the manner described for the Marshall test (B.1.3).

3. Place mixed material on a tray and return to the aggregate oven.

4. Repeat mixing operation for the second half of the specimen.

B.3.4 Compaction:

1. Place 4 x 72.5 kg (4 x 40 lb) masses on the hanger arrangement, turn on hydraulic power pack and set automatic counter for 30 passes.

2. Coat inside of mould with a mixture of limestone dust and water.

3. Transfer mixed material (2 halves) to the mould, spade with a spatula to form a level surface.

4. Wet roller segment with water, position mould beneath it and lower segment into mould until the full load has been transferred.

5. Set machine in motion. Upon completion of the operation, leave specimen in mould for approximately 1.5 hours.

6. Dismantle mould assembly, remove specimen and place it in a wooden box and store until testing. Mark specimen with the appropriate specimen identification number.

7. Reassemble mould and repeat operation with next specimen.

B.3.5 Determination of Specimen Density-Voids:

1. Remove each specimen in turn from its box and determine the mass of each to the nearest 1 gram.

2. Convert balance, by fitting metal sling arrangement and reweigh each specimen completely immersed in water at $20 \pm 1^{\circ}C$, to the nearest 1 gram, dry specimens and return to boxes.

3. Calculations are then carried out as for the Marshall test (B.1.5).

B.3.6 Wheel-Tracking Test:

1. Set up Tracking machine ready for testing:

   (i) Remove mould extension and load hanger, replace roller segment with the wheel arrangement, locate datum bar for transducer and locate steel block to apply the required contact pressure.

   (ii) Set position of knock-offs on table, such that the distance of travel of the mould is 250 mm.

   (iii) Set control valves on hydraulic power pack such that the speed of travel of the mould is 42 passes per minute.

2. Position one specimen in the mould and stack the remainder, in their boxes on the steel rack inside the temperature cabinet.

3. Set temperature control thermostat (45°C), switch on fan heater and electric pump, and leave overnight.

4. Prior to test, wire up recording equipment as shown in figure B.3.1 and calibrate as follows:

   (i) Switch on Transducer power supply and chart recorder (mains, chart and pen).

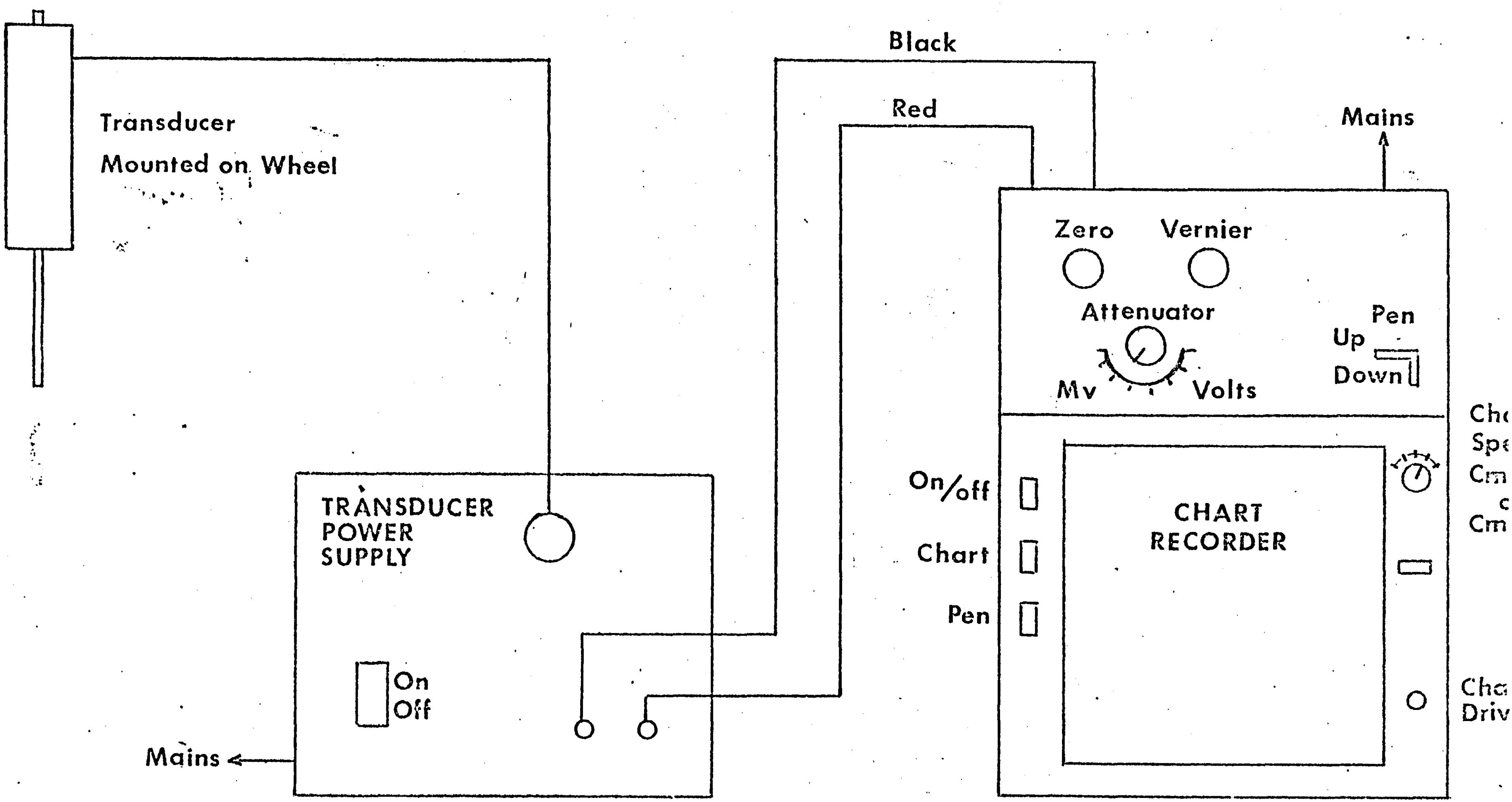
   (ii) Switch ATTENUATOR knob on chart recorder to 0.2 volt position and set chart speed at 60 cm/hr.

   (iii) Turn on hydraulic power pack and lower wheel/ transducer onto specimen, and locate it so the transducer is directly over the top of the incline.

   (iv) Place calibration block beneath transducer and use VERNIER knob to centre pen of recorder on the 10 inch line on the chart.

   (v) Remove calibration block and use ZERO knob on chart recorder to centre pen on zero line of the chart.

   (vi) Repeat (iv) and (v) until no further adjustment



Wheel – tracking Test Recording System

Fig. B

is required.

i.e. Pen is on the zero line of chart with the block removed and at the full scale deflection (10 in) of the chart with the block in position.

The recording equipment is now calibrated for a full-scale deflection of 25 mm.

4. Mark chart with the appropriate specimen identification number, set automatic counter for 2000 passes and commence test.

5. Upon completion of test, remove specimen and replace it with the next to be tested.

6. Allow 15 mins for the temperature to stabilise, check calibration of transducer and repeat test.

C. DATA RECORDING SHEETS

C.1 Introduction

Throughout the experimental work, numerical data was recorded on data sheets of the type presented in the following sections. These enabled all the relevant information regarding the composition and properties of the specimens tested to be stored away and later, quickly retrieved when further analysis was required.

C.2 Specimen Composition

COMPOSITION OF TEST SPECIMENS

For testing by:

BINDER	TYPE: SOURCE:	RELATIVE DENSITY		PENETRATION AT 25°C		SOFTENING POINT (°C)	

FILLER	TYPE: SOURCE:	RELATIVE DENSITY		%AGE PASSING 75 um sieve	

STONE	TYPE: SOURCE:	RELATIVE DENSITY		NOMINAL MAXIMUM SIZE (mm)	

SAND	TYPE: SOURCE:	RELATIVE DENSITY	

SIEVE SIZE.	%AGE PASSING
5mm	
2.36mm	
600um	
212um	
75um	

COMMENTS:

SPECIMEN I.D. NO.	TOTAL MASS (grams)	BINDER		FILLER		SAND		STONE	
		grams	%	grams	%	grams	%	grams	%

C.3 Laboratory Data

LABORATORY DATA

FOR TESTING BY:

DATE:

STONE:

SAND:

COMMENTS:

FILLER:

BINDER:

SPECIMEN IDENTIFICATION NUMBER	COMPACTION TEMPERATURE (°C)	MASS IN AIR (W) (grams)	MASS IN WATER (W_W) (grams)	SPECIMEN HEIGHT (H) (mm)	DISTANCE = MAX FORCE (inches)	DISTANCE = DEF AT MAX FORCE (cm)

C.4 Marshall Test Results

MARSHALL TEST RESULTS

STONE:

SAND:

FILLER:

BINDER:

DATE TESTED:

TEST TEMPERATURE:

COMPACTION:

COMMENTS:

SPECIMEN IDENTIFICATION NUMBER	COMPACTION TEMPERATURE (oC)	SPECIMEN HEIGHT (H) (mm)	MASS IN AIR (W) (grams)	MASS IN WATER (W_W) (grams)	SPECIMEN VOLUME (B) (ml)	RELATIVE DENSITY (S_M) (g1ml)	AGGREGATE DENSITY (S_A) (g1ml)	THEORETICAL MAX DENSITY (S_{TH})	VOIDS IN MIX (V_M) (per cent)	VOIDS IN AGGREGATE (V_A) (per cent)	VOIDS FILLED WITH BINDER (V_F) (percent	STABILITY (k_N)	CORRECTED STABILITY (S) (kN)	FLOW (F) (mm)	QUOTIENT (Q) (kN/mm)
MEAN															
MEAN															
MEAN															
MEAN															

C.5 Indirect-Tensile Test Results

INDIRECT-TENSILE TEST RESULTS

STONE:

SAND:

FILLER:

BINDER:

DATE TESTED:

TEST TEMPERATURE:

COMPACTION:

COMMENTS:

SPECIMEN IDENTIFICATION NUMBER	COMPACTION TEMPERATURE (°C)	SPECIMEN HEIGHT (H) (mm)	MASS IN AIR (W) (grams)	MASS IN WATER (W_W) (grams)	SPECIMEN VOLUME (B) (ml)	RELATIVE DENSITY (S_M) (glml)	AGGREGATE DENSITY (S_A) (glml)	THEORETICAL MAX DENSITY (S_{TH})	VOIDS IN MIX (V_M) (per cent)	VOIDS IN AGGREGATE (V_A) (per cent)	VOIDS FILLED WITH BINDER (V_F) (percent)	TENSILE STRENGTH (ITS) (N/mm^2)	TENSILE QUOTIENT (T) (N/mm^2)	VERTICAL DEF AT FAILURE (ΔD) (mm)
MEAN														
MEAN														
MEAN														
MEAN														

C.6 Wheel-Tracking Test Results

WHEEL - TRACKING RESULTS

STONE:

SAND:

FILLER:

BINDER:

DATE TESTED:

TEST TEMPERATURE:

COMPACTION:

COMMENTS:

SPECIMEN IDENTIFICATION NUMBER	COMPACTION TEMPERATURE (°C)	MASS IN AIR (W) (grams)	MASS IN WATER (W_W) (grams)	SPECIMEN VOLUME (B) (ml)	RELATIVE DENSITY (S_M) (g/ml)	AGGREGATE DENSITY (S_A) (g/ml)	THEORETICAL MAX DENSITY (S_{TH})	VOIDS IN MIX (V_M) (per cent)	VOIDS IN AGGREGATE (V_A) (per cent)	VOIDS FILLED WITH BINDER (V_F) (percent)	TRACKING RATE (mm/hr)	RUT DEPTH 100 PASSES (mm)	RUT DEPTH 1000 PASSES (mm)	RUT DEPTH END OF TEST (mm)

D. EXPERIMENTAL RESULTS.

D.1 MARSHALL TEST RESULTS:

D.1.1 Introduction:

Results obtained using the Marshall Test Method, as described in Chapter 5 are presented in the following Sections. Unless otherwise stated the results were obtained using the Marshall apparatus with load cell.

Tables containing results for all mixtures tested are included. The figures given in these tables are mean values for duplicate specimens of each mixture, unless otherwise stated. In each case the mixture is identified by the MIX CODE (see 4.6.3). Where the mean for duplicate specimens is given, the individual specimen numbers have been omitted. However, where results for individual specimens are reported, the full specimen identification has been included under SPECIMEN I.D.

The symbols at the head of each column (S_M, S_A, etc.) refer to the mixture properties determined, and are defined fully under NOTATION and in Chapter 6.

For selected stone contents the tabulated results have also been presented graphically to indicate how the various properties vary with respect to binder content (w_B). Each point on the graphs represents the mean value for duplicate specimens at that binder content.

D.1.2. Tables of Results - Sand A (Load Ring):

Table D.1.2.1: Sand A - 0% Stone (Load Ring)

MIX CODE	S_M	S_A	S	F
OA9.5M	2.044	1.850	2.91	3.7
OA10.0M	2.053	1.848	2.95	4.1
OA10.5M	2.053	1.838	3.21	3.9
OA11.0M	2.090	1.860	3.66	5.1
OA11.5M	2.098	1.857	4.96	5.5
OA12.0M	2.103	1.851	4.92	6.5
OA12.5M	2.103	1.840	5.22	7.5
OA13.0M	2.088	1.817	4.69	7.7
OA13.5M	2.064	1.786	3.97	8.9
OA14.0M	2.040	1.754	3.25	10.8
OA14.5M	2.011	1.720	2.43	11.3
OA15.0M	1.967	1.672	2.15	10.9

Table D.1.2.2. : Sand A - 30% Stone (Load Ring)

MIX CODE	S_M	S_A	S	F
30A6.0M	2.184	2.053	5.62	3.9
30A6.5M	2.213	2.069	5.80	3.7
30A7.0M	2.224	2.069	5.78	3.9
30A7.5M	2.222	2.055	5.20	4.4
30A8.0M	2.244	2.064	5.50	4.2
30A8.5M	2.250	2.059	5.55	5.3
30A9.0M	2.246	2.043	6.40	6.2
30A9.5M	2.236	2.024	5.79	6.9
30A10.0M	2.220	1.999	4.83	6.7
30A10.5M	2.190	1.961	4.02	7.7
30A11.0M	2.185	1.944	3.38	10.2
30A11.5M	2.157	1.909	2.96	11.6

Table D.1.2.3. : Sand A - 40% Stone (Load Ring)

40A5.5M	2.240	2.117	7.75	3.9
40A6.5M	2.273	2.126	7.57	4.2
40A7.0M	2.284	2.125	8.07	4.1
40A7.5M	2.291	2.119	8.27	5.0
40A8.0M	2.294	2.110	7.82	6.8
40A9.0M	2.256	2.053	5.53	8.6

Table D.1.2.4. : Sand A - 0% Stone (Single Binder Content - Load Ring)

SPECIMEN I.D.	S_M	S_A	V_M	V_A	V_F	S	F	Q
OA12.0M1	2.102	1.850	5.2	29.7	82.6	5.02	6.9	0.72
OA12.0M2	2.099	1.847	5.3	29.8	82.1	4.71	6.9	0.68
OA12.0M3	2.101	1.849	5.3	29.7	82.3	4.65	7.3	0.64
OA12.0M4	2.104	1.851	5.1	29.6	82.7	4.70	6.8	0.69
OA12.0M5	2.092	1.841	5.7	30.0	81.1	4.67	7.2	0.65
OA12.0M6	2.092	1.841	5.6	30.0	81.2	4.68	7.6	0.62
OA12.0M7	2.098	1.846	5.4	29.8	81.9	4.68	8.1	0.58
OA12.0M8	2.096	1.844	5.5	29.9	81.7	4.92	7.2	0.68
OA12.0M9	2.102	1.850	5.2	29.7	82.5	5.07	8.4	0.60
OA12.0M10	2.095	1.844	5.5	29.9	81.6	4.74	7.3	0.65
OA12.0M11	2.096	1.845	5.5	29.9	81.7	4.91	7.3	0.68
OA12.0M12	2.098	1.846	5.4	29.8	82.0	4.86	7.9	0.62

MEAN	2.098	1.846	5.4	29.8	82.0	4.80	7.4	0.65	
STANDARD DEVIATION	0.004	0.003	0.2	0.1	0.5	0.15	0.5	0.04	
COEFFICIENT OF VARIATION	0.2	0.2	3.7	0.3	0.6	3.1	6.8	6.2	%

Table D.1.2.5. : Sand A - 30% Stone (Single Binder Content - Load Ring)

SPECIMEN I.D.	S_M	S_A	V_M	V_A	V_F	S	F	Q
30A8.0M1	2.244	2.065	5.3	22.7	76.7	6.01	3.8	1.59
30A8.0M2	2.246	2.066	5.2	22.7	77.0	6.31	3.7	1.71
30A8.0M3	2.244	2.065	5.3	22.7	76.7	5.68	4.0	1.41
30A8.0M4	2.254	2.074	4.9	22.4	78.3	6.64	4.2	1.58
30A8.0M5	2.243	2.064	5.3	22.8	76.6	6.18	4.1	1.52
30A8.0M6	2.244	2.065	5.3	22.7	76.7	5.76	4.2	1.37
30A8.0M7	2.244	2.064	5.3	22.7	76.7	6.17	4.0	1.54
30A8.0M8	2.243	2.064	5.3	22.8	76.6	6.45	4.6	1.39
30A8.0M9	2.242	2.062	5.4	22.8	76.4	5.75	4.6	1.25
30A8.0M10	2.234	2.055	5.7	23.1	75.2	6.15	3.7	1.65
30A8.0M11	2.230	2.052	5.9	23.2	74.6	NO DATA		
30A8.0M12	2.238	2.059	5.6	22.9	75.8	6.56	4.1	1.62

MEAN	2.242	2.063	5.4	22.8	76.4	6.15	4.1	1.51	
STANDARD DEVIATION	0.006	0.006	0.3	0.2	0.9	0.33	0.3	0.14	
COEFFICIENT OF VARIATION	0.3	0.3	5.6	0.9	1.2	5.4	7.3	9.3	%

D.1.3. Tables of Results - Sand A:

Table D.1.3.1. : Sand A - 0% Stone (Series No. 1)

MIX CODE	S_M	S_A	V_M	V_A	V_F	S	F	Q
0A9.5M	2.037	1.844	11.1	29.9	62.8	3.34	5.6	0.60
0A10.0M	2.069	1.862	9.1	29.2	68.7	3.70	6.2	0.60
0A10.5M	2.068	1.851	8.6	29.6	71.2	3.87	7.6	0.52
0A11.0M	2.085	1.855	7.2	29.5	75.5	4.07	6.5	0.63
0A11.5M	2.104	1.862	5.7	29.2	80.4	5.21	6.7	0.77
0A12.0M	2.105	1.853	5.1	29.6	82.9	5.01	7.4	0.67
0A12.5M	2.104	1.841	4.5	30.0	85.0	4.38	9.3	0.48
0A13.0M	2.096	1.823	4.3	30.7	86.2	4.19	11.1	0.38
0A13.5M	2.089	1.800	4.3	31.6	86.3	3.48	12.3	0.29
0A14.0M	2.060	1.772	4.7	32.7	85.7	3.07	14.0	0.22
0A14.5M	2.027	1.753	5.6	34.1	83.6	2.24	13.3	0.17
0A15.0M	2.030	1.726	4.9	34.4	85.9	2.10	14.9	0.14

Table D.1.3.2. : Sand A - 0% Stone (Series No. 2)

MIX CODE	S_M	S_A	V_M	V_A	V_F	S	F	Q
OA9.5M	2.047	1.852	10.7	29.6	63.8	4.81	5.6	0.86
OA10.0M	2.058	1.852	9.6	29.6	67.6	4.64	4.9	0.95
OA10.5M	2.085	1.866	7.8	29.1	73.1	5.17	5.2	1.01
OA11.0M	2.094	1.863	6.8	29.2	76.6	5.64	5.3	1.06
OA11.5M	2.095	1.854	6.2	29.5	79.2	5.23	5.8	0.90
OA12.0M	2.104	1.852	5.1	29.6	82.7	5.64	6.4	0.88
OA12.5M	2.106	1.843	4.4	30.0	85.3	5.86	6.9	0.85
OA13.0M	2.089	1.813	4.8	31.1	84.6	5.16	7.9	0.65
OA13.5M	2.069	1.790	4.9	32.0	84.8	4.21	8.8	0.48
OA14.0M	2.061	1.772	4.6	32.7	85.8	3.51	9.3	0.38
OA14.5M	2.033	1.738	5.3	33.9	84.4	3.01	10.3	0.29

Table D.1.3.3. : Sand A - 5% Stone

MIX CODE	S_M	S_A	V_M	V_A	V_F	S	F	Q
5A9.0M	2.091	1.903	9.5	27.8	65.8	3.93	4.7	0.84
5A10.0M	2.118	1.906	7.1	27.7	74.3	4.45	4.7	0.95
5A10.5M	2.123	1.900	6.6	27.7	76.2	5.12	5.0	1.02
5A11.0M	2.127	1.893	5.4	28.2	80.7	5.04	6.3	0.80
5A11.5M	2.125	1.881	4.9	28.7	82.8	4.97	7.1	0.71
5A12.0M	2.118	1.864	4.6	29.3	84.2	5.04	7.7	0.66
5A13.0M	2.083	1.812	5.0	31.2	84.2	3.48	8.8	0.40

Table D.1.3.4. : Sand A - 10% Stone

10A8.5M	2.117	1.938	9.1	26.6	65.8	5.63	6.4	0.87
10A9.5M	2.142	1.939	6.8	26.5	74.5	5.48	5.4	1.02
10A10.0M	2.154	1.939	5.6	26.5	78.8	5.63	5.9	0.97
10A10.5M	2.156	1.930	4.9	26.9	81.7	6.11	5.8	1.05
10A11.0M	2.159	1.921	4.2	27.2	84.7	6.39	6.5	0.99
10A11.5M	2.143	1.896	4.2	28.2	84.9	5.77	7.6	0.77
10A12.5M	2.111	1.847	4.4	30.0	85.3	4.24	8.4	0.51

Table D.1.3.5. : Sand A - 20% Stone

MIX CODE	S_M	S_A	V_M	V_A	V_F	S	F	Q
20A7.0M	2.144	1.994	10.1	24.7	59.0	5.41	4.0	1.56
20A8.0M	2.177	2.003	7.4	24.4	69.4	5.94	4.0	1.52
20A8.5M	2.186	2.001	6.4	24.5	73.7	6.77	3.9	1.75
20A9.0M	2.194	1.996	5.4	24.6	77.9	6.60	4.4	1.52
20A9.5M	2.197	1.980	5.1	25.3	80.0	5.91	5.0	1.18
20A10.0M	2.190	1.971	4.3	25.6	83.1	5.03	5.5	0.92
20A11.0M	2.160	1.922	4.4	27.4	83.1	3.85	7.8	0.49

Table D.1.3.6. : Sand A - 30% Stone
(Series No. 1)

30A5.5M	2.189	2.068	10.4	22.1	52.8	8.80	4.0	2.23
30A6.0M	2.201	2.069	9.3	22.1	58.0	7.35	4.1	1.78
30A6.5M	2.211	2.068	8.2	22.2	63.0	7.99	4.3	1.85
30A7.0M	2.235	2.078	6.6	21.8	69.8	7.92	3.8	2.08
30A7.5M	2.249	2.080	5.3	21.7	75.5	8.51	4.0	2.15
30A8.0M	2.253	2.073	4.5	22.0	79.6	8.13	5.5	1.50
30A8.5M	2.248	2.057	4.0	22.6	82.2	7.09	5.6	1.27
30A9.0M	2.246	2.044	3.5	23.1	85.0	6.96	5.8	1.23
30A9.5M	2.214	2.004	4.2	24.6	83.1	4.71	7.5	0.63
30A10.0M	2.213	1.992	3.5	25.0	85.9	4.38	7.1	0.62
30A10.5M	2.174	1.945	4.6	26.8	82.8	3.21	8.0	0.41
30A11.0M	2.154	1.918	4.8	27.8	82.7	2.41	8.6	0.29

Table D.1.3.7. : Sand A - 30% Stone
(Series No. 2)

MIX CODE	S_M	S_A	V_M	V_A	V_F	S	F	Q
30A6.0M	2.189	2.058	10.2	23.0	55.5	6.78	3.4	1.99
30A6.5M	2.205	2.062	8.9	22.8	61.0	5.05	3.6	1.42
30A7.0M	2.237	2.081	6.9	22.1	68.8	5.87	3.1	1.88
30A7.5M	2.250	2.081	5.7	22.1	74.1	7.10	3.2	2.27
30A8.0M	2.254	2.073	4.9	22.4	78.1	6.75	3.9	1.73
30A8.5M	2.252	2.061	4.3	22.9	81.2	5.88	5.4	1.15
30A9.0M	2.248	2.046	3.8	23.5	83.7	5.37	5.7	0.94
30A9.5M	2.229	2.018	3.9	24.5	83.9	4.65	6.0	0.79
30A10.0M	2.226	2.003	3.4	25.0	86.3	5.07	6.5	0.79
30A10.5M	2.203	1.972	3.8	26.2	85.7	3.69	7.9	0.48
30A11.0M	2.184	1.944	4.0	27.3	85.5	3.15	7.8	0.41
30A11.5M	2.157	1.909	4.5	28.6	84.3	2.61	10.8	0.24

Table D.1.3.8. : Sand A - 40% Stone

40A5.5M	2.256	2.131	7.9	20.0	60.3	9.63	3.5	2.77
40A6.5M	2.295	2.145	5.0	19.5	74.4	9.39	4.4	2.13
40A7.0M	2.298	2.138	4.2	19.8	79.0	9.30	4.6	2.06
40A7.5M	2.299	2.127	3.5	20.2	82.9	8.06	5.1	1.57
40A8.0M	2.294	2.110	3.0	20.8	85.6	6.76	6.3	1.08
40A8.5M	2.270	2.077	3.3	22.1	85.0	5.65	6.6	0.86
40A9.5M	2.245	2.032	3.1	23.8	87.0	3.90	8.4	0.48

Table D.1.3.9. : Sand A - 55% Stone
(Series No. 1)

MIX CODE	S_M	S_A	V_M	V_A	V_F	S	F	Q
55A3.5M	2.279	2.199	10.1	17.8	44.1	7.52	3.4	2.24
55A4.5M	2.285	2.182	8.5	18.4	54.0	7.85	4.2	1.88
55A5.0M	2.308	2.193	6.9	18.1	62.1	8.25	3.2	2.59
55A5.5M	2.314	2.186	6.0	18.3	67.4	9.22	4.0	2.29
55A6.0M	2.333	2.193	4.5	18.1	75.2	9.42	4.4	2.16
55A6.5M	2.347	2.195	3.2	18.0	82.2	9.95	4.9	2.03
55A7.5M	2.336	2.161	2.3	19.3	88.2	7.80	7.5	1.04

Table D.1.3.10. : Sand A - 55% Stone
(Series No. 2)

55A3.5M	2.202	2.125	13.1	20.6	36.4	6.11	3.0	2.08
55A4.5M	2.277	2.174	8.8	18.8	53.0	6.24	3.5	1.81
55A5.0M	2.302	2.187	7.1	18.3	61.1	7.31	3.4	2.16
55A5.5M	2.322	2.195	5.6	18.0	68.9	10.60	4.0	2.64
55A6.0M	2.334	2.194	4.4	18.0	75.4	9.03	4.7	1.94
55A6.5M	2.347	2.194	3.3	18.1	82.0	8.70	5.1	1.70
55A7.5M	2.335	2.160	2.3	19.3	88.1	7.16	7.0	1.03

Table D.1.3.11. : Sand A - 0% Stone (Single Binder Content).

SPECIMEN I.D.	S_M	S_A	V_M	V_A	V_F	S	F	Q
OA12.0M13	2.103	1.851	5.2	29.7	82.6	4.81	6.2	0.78
OA12.0M14	2.096	1.845	5.5	29.9	81.7	4.85	6.2	0.78
OA12.0M15	2.096	1.844	5.5	29.9	81.7	4.45	6.6	0.68
OA12.0M16	2.101	1.849	5.2	29.7	82.4	-	-	-
OA12.0M17	2.100	1.848	5.3	29.8	82.2	5.14	7.9	0.65
OA12.0M18	2.090	1.839	5.7	30.1	80.9	5.44	6.9	0.79
OA12.0M19	2.096	1.844	5.5	29.9	81.7	5.82	7.6	0.77
OA12.0M20	2.098	1.847	5.4	29.8	82.0	5.59	7.5	0.75
OA12.0M21	2.098	1.856	5.4	29.8	82.0	5.53	7.3	0.75
OA12.0M22	2.097	1.845	5.4	29.9	81.8	5.60	6.7	0.83
OA12.0M23	2.103	1.851	5.2	29.7	82.6	5.92	6.1	0.98
OA12.0M24	2.103	1.851	5.1	29.6	82.7	5.13	6.8	0.76

MEAN	2.098	1.847	5.4	29.8	82.0	5.30	6.9	0.78	
STANDARD DEVIATION	0.004	0.004	0.2	0.1	0.5	0.46	0.6	0.09	
COEFFICIENT OF VARIATION	0.2	0.2	3.7	0.3	0.6	8.7	8.7	11.5	%
RANGE	0.013	0.012	0.6	0.5	1.8	14.70	1.8	0.33	

Table D.1.3.12. : Sand A - 30% Stone (Single Binder Content).

SPECIMEN I.D.	S_M	S_A	V_M	V_A	V_F	S	F	Q
30A8.0M13	2.251	2.071	5.0	22.5	77.8	6.75	4.0	1.70
30A8.0M14	2.249	2.069	5.1	22.6	77.4	6.46	4.0	1.63
30A8.0M15	2.259	2.078	4.7	22.2	78.9	7.00	4.0	1.77
30A8.0M16	2.248	2.068	5.1	22.6	77.3	6.84	4.1	1.69
30A8.0M17	2.245	2.065	5.3	22.7	76.9	6.49	3.7	1.77
30A8.0M18	2.253	2.073	4.9	22.4	78.1	7.04	4.2	1.67
30A8.0M19	2.236	2.057	5.7	23.0	75.4	6.41	4.0	1.60
30A8.0M20	2.250	2.070	5.0	22.5	77.7	6.90	3.5	1.95
30A8.0M21	2.251	2.070	5.0	22.5	77.7	7.06	3.9	1.80
30A8.0M22	2.238	2.059	5.6	23.0	75.7	5.82	3.6	1.61
30A8.0M23	2.232	2.053	5.8	23.1	74.9	5.73	3.5	1.63
30A8.0M24	2.252	2.072	4.9	22.4	78.0	6.48	3.6	1.80

MEAN	2.247	2.067	5.2	22.6	77.2	6.58	3.8	1.72
STANDARD DEVIATION	0.008	0.007	0.4	0.3	1.2	0.45	0.3	0.10
COEFFICIENT OF VARIATION	0.4	0.3	7.7	1.3	1.6	6.8	7.9	5.8
RANGE	0.027	0.025	1.1	0.9	4.0	13.30	0.7	0.35

%

D.1.4 Graphical Presentation - Sand A

Figure D.1.4.1

Marshall Results : Sand A - 0% Stone

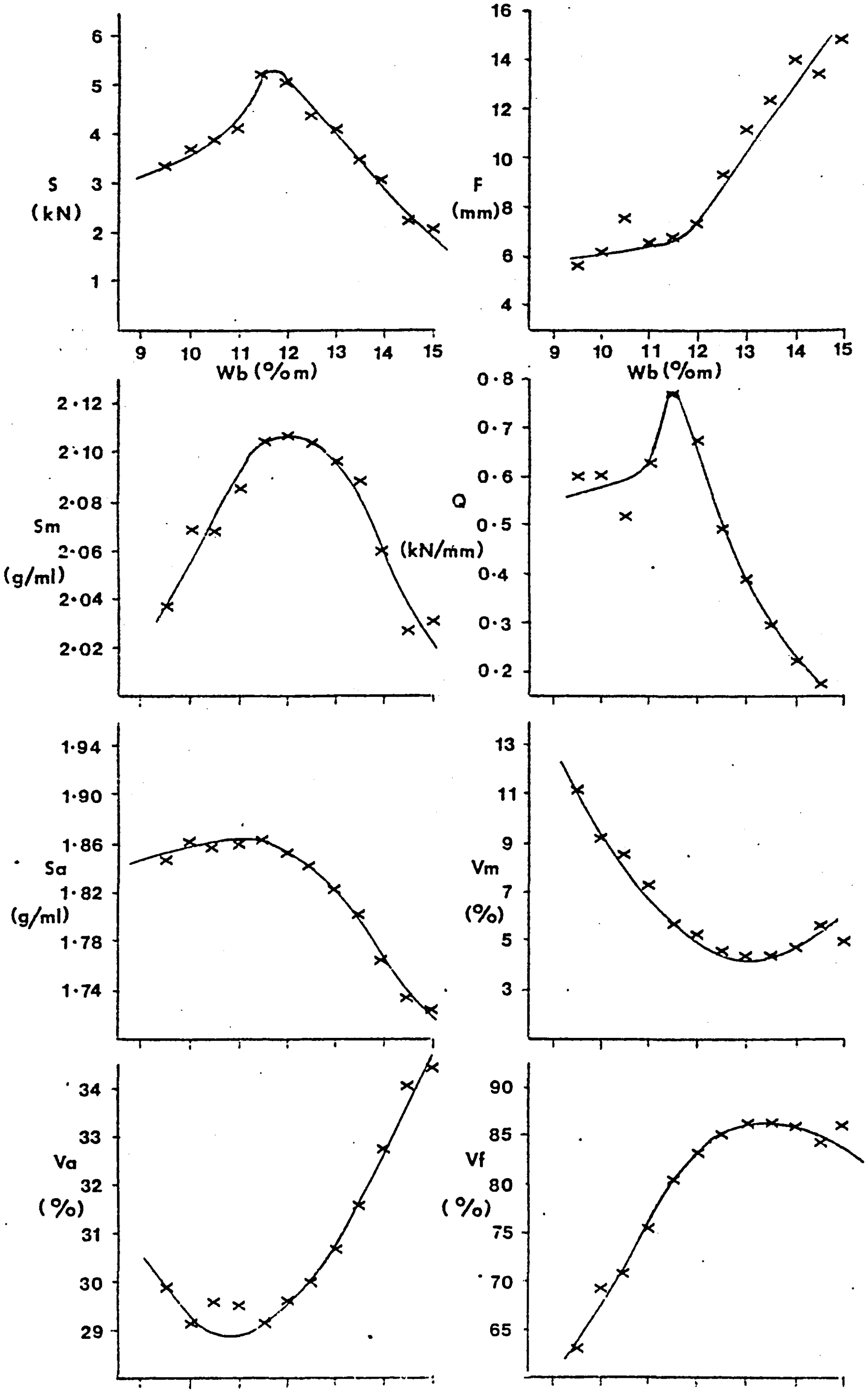


Figure D.1.4.2

Marshall Results : Sand A - 30% Stone

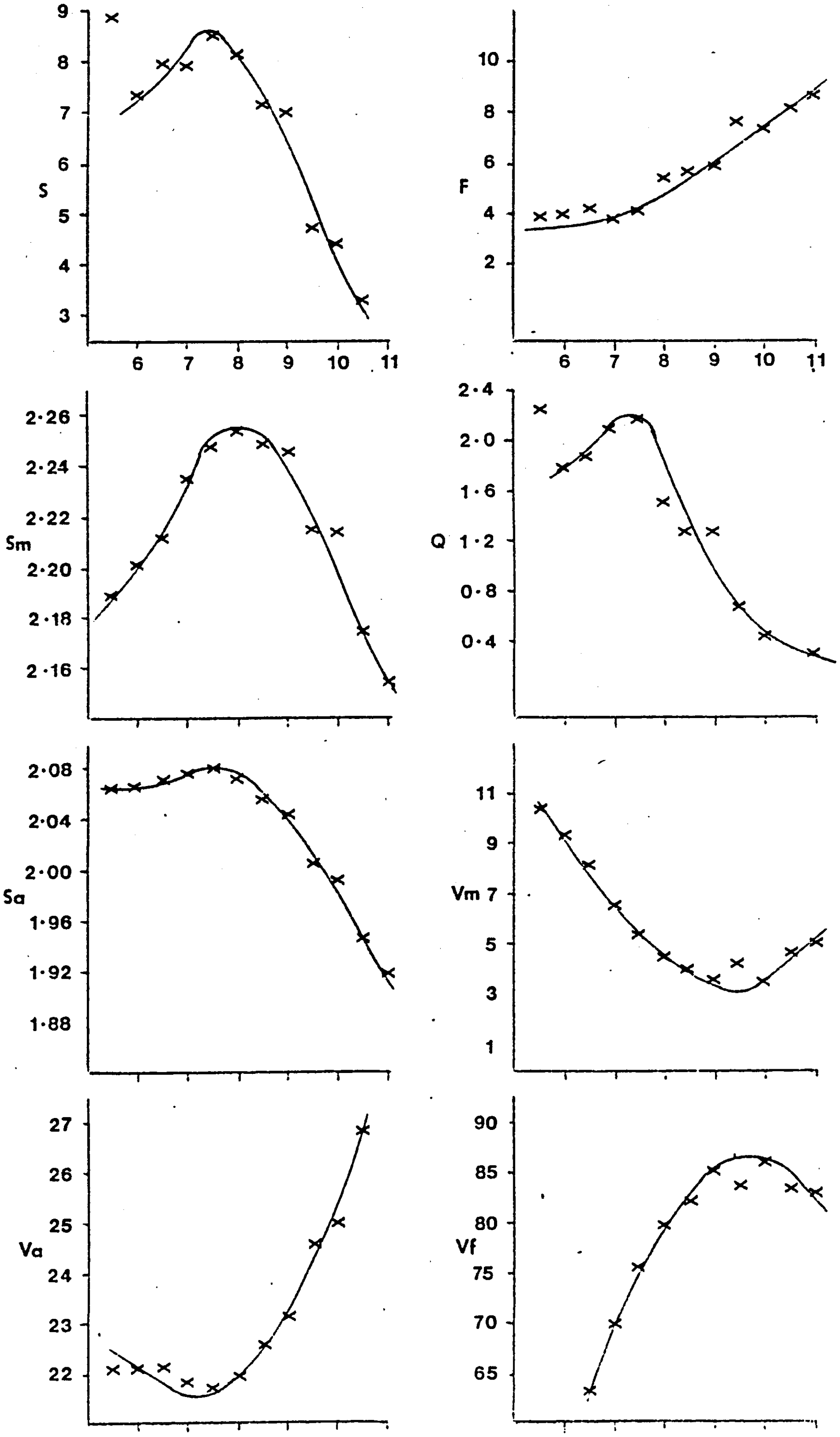


Figure D.1.4.3

Marshall Results : Sand A - 40% Stone

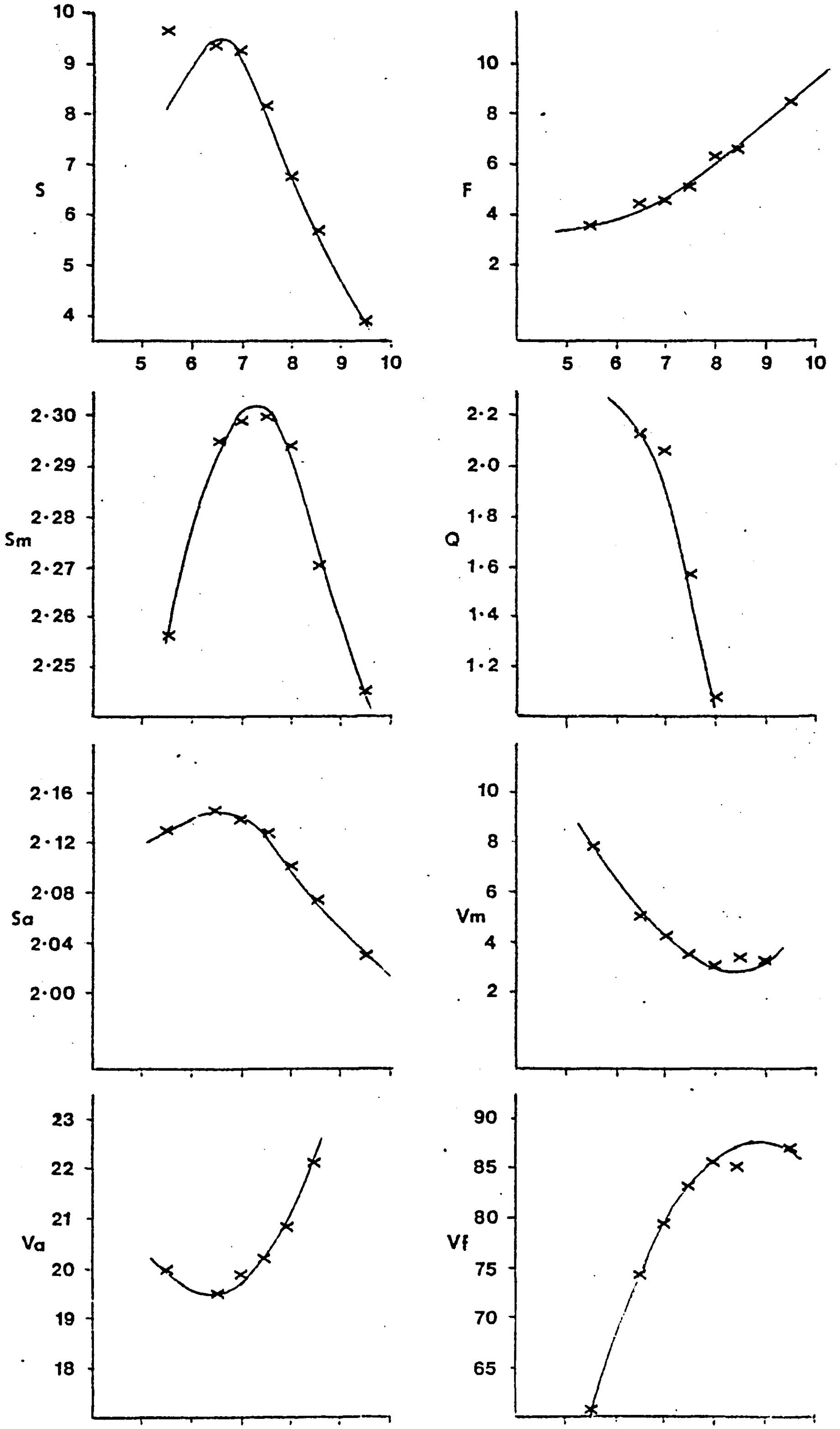
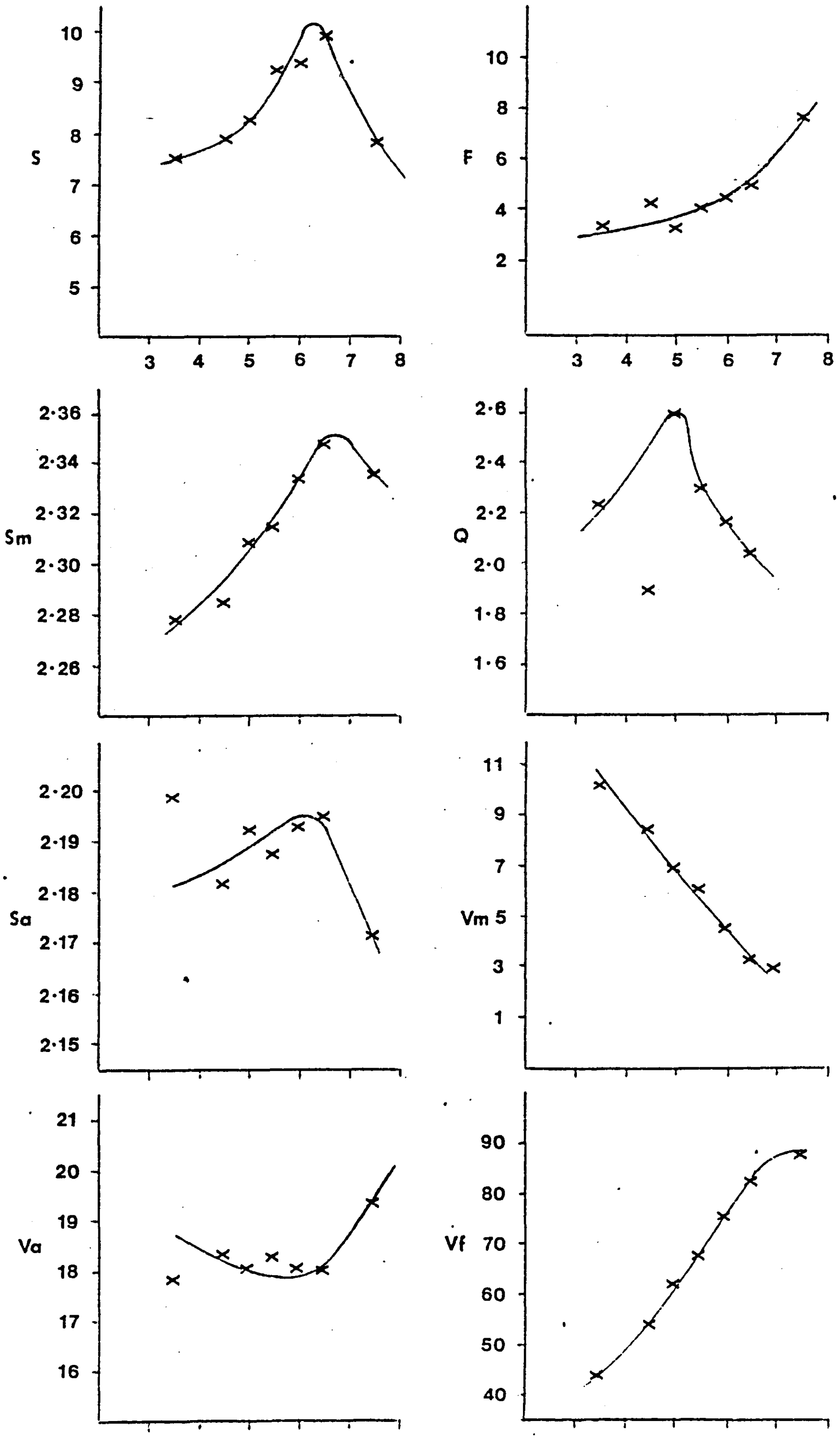


Figure D.1.4.4

Marshall Results : Sand A - 55% Stone



D.1.5. Co-operative Work at E.R.C.A.

Tables of Results - Sand A.

Table D.1.5.1. : Sand A - 0% Stone (E.R.C.A.)

MIX CODE	S_M	S_A	V_M	V_A	V_F	S	F	Q
OA9.5M	2.054	1.859	10.4	29.4	64.5	3.58	3.5	1.05
OA10.0M	2.075	1.867	8.9	29.1	69.3	3.92	3.9	1.00
OA10.5M	2.088	1.869	7.7	29.0	73.5	3.82	4.6	0.83
OA11.0M	2.087	1.857	7.1	29.4	75.8	3.70	4.6	0.80
OA11.5M	2.098	1.857	6.0	29.3	79.6	5.19	5.0	1.04
OA12.0M	2.094	1.843	5.6	30.0	81.5	5.43	5.7	0.96
OA12.5M	2.097	1.835	4.8	30.3	84.1	4.89	5.6	0.88
OA13.0M	2.085	1.814	4.7	31.1	84.8	4.29	6.1	0.71
OA13.5M	2.074	1.794	4.6	31.8	85.4	3.72	7.1	0.53
OA14.0M	2.059	1.771	4.7	32.7	85.6	3.23	7.7	0.42
OA14.5M	2.036	1.741	5.2	33.8	84.7	2.60	7.8	0.33
OA15.0M	2.009	1.708	5.9	35.1	83.3	2.19	8.4	0.26

Table D.1.5.2. : Sand A - 0% Stone
(Single Binder Content - E.R.C.A.)

SPECIMEN I.D.	S_M	S
OA12.0M25	2.089	5.39
OA12.0M26	2.092	5.20
OA12.0M27	2.092	5.32
OA12.0M28	2.095	5.21
OA12.0M29	2.099	5.44
OA12.0M30	2.097	5.29

D.1.6. Tables of Results - Sand B "As Received".

Table D.1.6.1. : Sand B "As Received" - 0% Stone

MIX CODE	S_M	S_A	V_M	V_A	V_F	S	F	Q
0B^{1}4.5M	2.123	2.028	13.7	23.0	40.4	4.64	3.8	1.27
0B^{1}5.0M	2.167	2.057	11.3	21.8	48.3	5.17	3.9	1.35
0B^{1}5.5M	2.209	2.088	8.9	20.7	57.0	5.67	4.3	1.33
0B^{1}6.0M	2.252	2.117	6.5	19.6	66.9	5.61	4.2	1.34
0B^{1}6.5M	2.265	2.118	5.3	19.6	73.1	5.62	4.7	1.22
0B^{1}7.0M	2.272	2.113	4.6	20.0	77.2	5.16	5.5	0.95
0B^{1}7.5M	2.261	2.091	4.1	20.6	80.0	4.87	6.7	0.74
0B^{1}8.0M	2.252	2.072	3.8	21.3	82.2	4.00	9.4	0.43
0B^{1}8.5M	2.245	2.054	3.4	22.0	84.4	3.52	8.9	0.40
0B^{1}9.0M	2.218	2.019	3.9	23.3	83.2	2.83	14.4	0.20
0B^{1}9.5M	2.203	1.994	4.0	24.3	83.7			

Table D.1.6.2. : Sand B "As Received" - 10% Stone

10B^{1}4.0M	2.187	2.100	12.0	20.5	41.5	5.35	5.7	0.95
10B^{1}5.0M	2.278	2.165	7.0	18.0	61.4	6.83	4.5	1.54
10B^{1}5.5M	2.293	2.166	5.7	18.0	68.2	6.27	5.1	1.25
10B^{1}6.0M	2.304	2.165	4.6	18.0	74.6	5.91	5.4	1.11
10B^{1}6.5M	2.306	2.156	3.8	18.4	79.2	5.03	5.8	0.86
10B^{1}7.5M	2.297	2.125	2.8	19.5	85.6	3.83	7.7	0.50

Table D.1.6.3. : Sand B "As Received" - 20% Stone

MIX CODE	S_M	S_A	V_M	V_A	V_F	S	F	Q
20B^{1}3.5M	2.237	2.159	10.9	18.5	41.1	7.42	4.3	1.74
20B^{1}4.0M	2.282	2.191	8.4	17.3	51.3	7.06	4.7	1.53
20B^{1}4.5M	2.324	2.219	6.1	16.2	62.7	7.41	4.7	1.59
20B^{1}5.0M	2.319	2.204	5.5	16.8	67.0	6.44	4.5	1.46
20B^{1}5.5M	2.325	2.198	4.6	17.0	72.9	6.12	4.8	1.31
20B^{1}6.5M	2.305	2.155	3.3	17.9	81.8	5.80	6.6	0.88

Table D.1.6.4. : Sand B "As Received" - 30% Stone

30B^{1}3.0M	2.263	2.195	10.8	17.4	38.0	6.99	3.2	2.18
30B^{1}3.5M	2.308	2.227	8.3	16.2	48.5	8.64	3.6	2.43
30B^{1}4.0M	2.349	2.255	6.0	15.1	60.4	8.83	3.7	2.39
30B^{1}4.5M	2.347	2.247	5.4	15.6	65.7	7.05	4.0	1.76
30B^{1}5.0M	2.358	2.240	4.2	15.7	73.0	6.43	4.3	1.51
30B^{1}5.5M	2.373	2.242	2.9	15.6	81.2	5.86	5.5	1.07
30B^{1}6.0M	2.359	2.218	2.8	16.5	83.2	5.42	7.1	0.77
30B^{1}6.5M	2.345	2.193	2.7	17.5	84.8	4.75	8.7	0.55
30B^{1}7.0M	2.334	2.171	2.4	18.3	86.9	4.13	9.7	0.43

D.1.7. Tables of Results - Sand B.

Table D.1.7.1. : Sand B - 0% Stone
(Series No. 1)

MIX CODE	S_M	S_A	V_M	V_A	V_F	S	F	Q
OB5.5M	2.133	2.015	12.1	23.4	48.6	5.05	3.0	1.67
OB6.5M	2.196	2.053	8.2	22.0	62.9	4.82	3.6	1.33
OB7.0M	2.216	2.061	6.7	21.7	69.4	5.00	3.9	1.29
OB7.5M	2.216	2.050	6.0	22.1	72.9	4.52	4.3	1.06
OB8.0M	2.221	2.043	5.1	22.4	77.1	4.60	5.0	0.94
OB8.5M	2.222	2.033	4.4	22.8	80.5	3.62	5.6	0.72
OB9.5M	2.219	2.008	3.3	23.7	86.3	3.72	7.0	0.54

Table D.1.7.2. : Sand B - 0% Stone
(Series No. 2)

OB5.5M	2.150	2.032	11.4	22.8	50.3	4.55	4.1	1.12
OB6.5M	2.207	2.063	7.7	21.6	64.4	4.90	4.0	1.25
OB7.0M	2.221	2.066	6.5	21.5	70.1	4.52	3.8	1.21
OB7.5M	2.235	2.067	5.2	21.5	75.8	4.45	5.5	0.84
OB8.0M	2.235	2.056	4.5	21.9	79.3	4.33	5.5	0.79
OB8.5M	2.234	2.044	3.9	22.4	82.5	4.05	6.2	0.66
OB9.0M	2.223	2.023	3.7	23.2	83.9	3.65	6.7	0.55

Table D.1.7.3. : Sand B - 10% Stone

MIX CODE	S_M	S_A	V_M	V_A	V_F	S	F	Q
10B4.5M	2.162	2.065	12.1	21.5	43.9	4.14	3.6	1.15
10B5.5M	2.187	2.067	9.8	21.5	54.4	5.08	3.6	1.41
10B6.0M	2.225	2.092	7.6	20.5	63.2	5.26	3.8	1.38
10B6.5M	2.235	2.089	6.5	20.6	68.5	5.36	3.7	1.45
10B7.0M	2.244	2.087	5.4	20.7	73.8	4.67	4.6	1.02
10B7.5M	2.234	2.044	3.9	22.3	82.6	3.87	6.3	0.61
10B8.5M	2.214	2.026	4.7	23.0	79.5	3.54	6.4	0.55

Table D.1.7.4. : Sand B - 20% Stone

20B4.0M	2.124	2.039	14.4	22.7	36.4	5.09	2.7	1.89
20B5.0M	2.189	2.079	10.5	21.1	50.3	5.28	2.5	2.11
20B5.5M	2.231	2.108	8.1	20.0	59.0	5.72	3.0	1.91
20B6.0M	2.253	2.118	6.6	19.7	66.6	5.70	3.5	1.63
20B6.5M	2.266	2.119	5.4	20.1	72.8	5.46	4.0	1.37
20B7.0M	2.263	2.105	4.8	20.2	76.3	4.94	4.4	1.12
20B8.0M	2.258	2.078	3.7	21.2	82.7	4.00	6.1	0.66

Table D.1.7.5. : Sand B - 30% Stone

MIX CODE	S_M	S_A	V_M	V_A	V_F	S	F	Q
30B4.0M	2.269	2.178	8.8	17.7	49.9	7.08	3.1	2.27
30B4.5M	2.282	2.180	7.6	17.6	56.6	7.12	2.9	2.50
30B5.0M	2.305	2.190	6.1	17.2	64.9	6.75	3.1	2.20
30B5.5M	2.312	2.185	5.1	17.4	70.8	6.47	4.0	1.62
30B6.0M	2.303	2.165	4.8	18.2	73.7	5.58	4.0	1.39
30B6.5M	2.295	2.146	4.4	18.9	76.6	4.24	5.7	0.75
30B7.5M	2.286	2.114	3.5	20.1	82.7	3.50	6.0	0.59

Table D.1.7.6. : Sand B - 38% Stone

38B3.0M	2.241	2.173	11.5	18.1	36.1	4.45	3.8	1.17
38B4.0M	2.286	2.194	8.4	17.3	51.3	6.38	4.0	1.59
38B4.5M	2.319	2.214	6.4	16.6	61.2	7.19	3.8	1.92
38B5.0M	2.340	2.220	5.0	16.3	69.4	6.74	3.5	1.91
38B5.5M	2.338	2.210	4.3	16.8	74.5	6.43	4.5	1.44
38B6.0M	2.339	2.199	3.6	17.2	79.4	5.74	5.0	1.15
38B7.0M	2.318	2.156	3.1	18.8	83.8	4.92	7.3	0.68

Table D.1.7.7. : Sand B - 55% Stone

55B3.0M	2.333	2.262	8.5	15.2	44.6	6.32	3.5	1.83
55B3.5M	2.364	2.281	6.5	14.5	55.2	7.88	3.4	2.37
55B4.0M	2.377	2.282	5.3	14.5	63.6	8.06	4.0	2.04
55B4.5M	2.384	2.277	4.3	14.7	70.7	7.63	4.1	1.74
55B5.0M	2.397	2.276	3.1	14.7	79.2	8.38	4.8	1.76
55B5.5M	2.392	2.261	2.6	15.3	83.3	6.95	5.6	1.24
55B6.5M	2.363	2.210	2.4	17.3	86.3	5.57	8.1	0.69

D.1.8 Graphical Presentation - Sand B

Figure D.1.8.1

Marshall Results : Sand B - 0% Stone

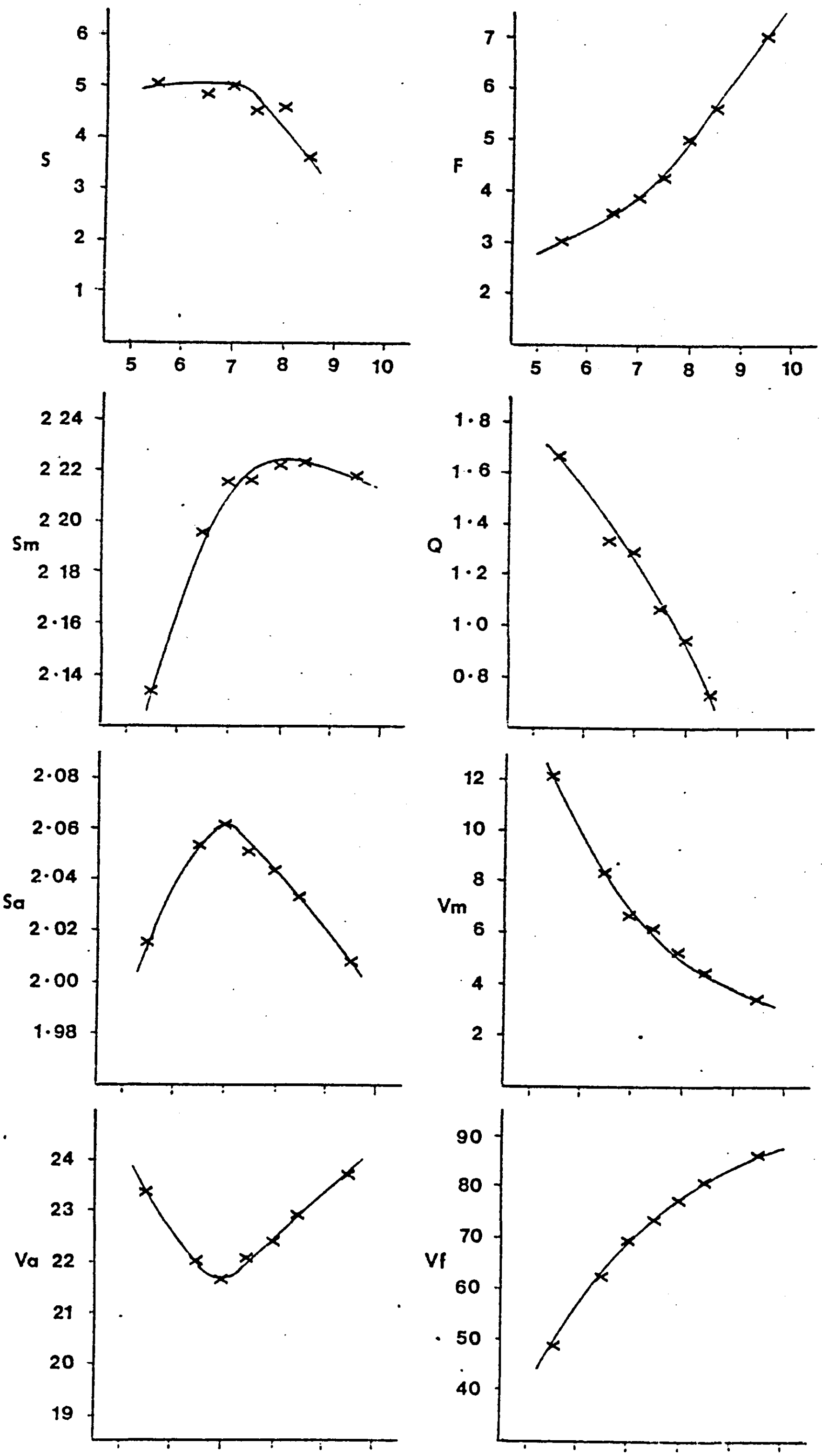


Figure D.1.8.2

Marshall Results : Sand B - 30% Stone

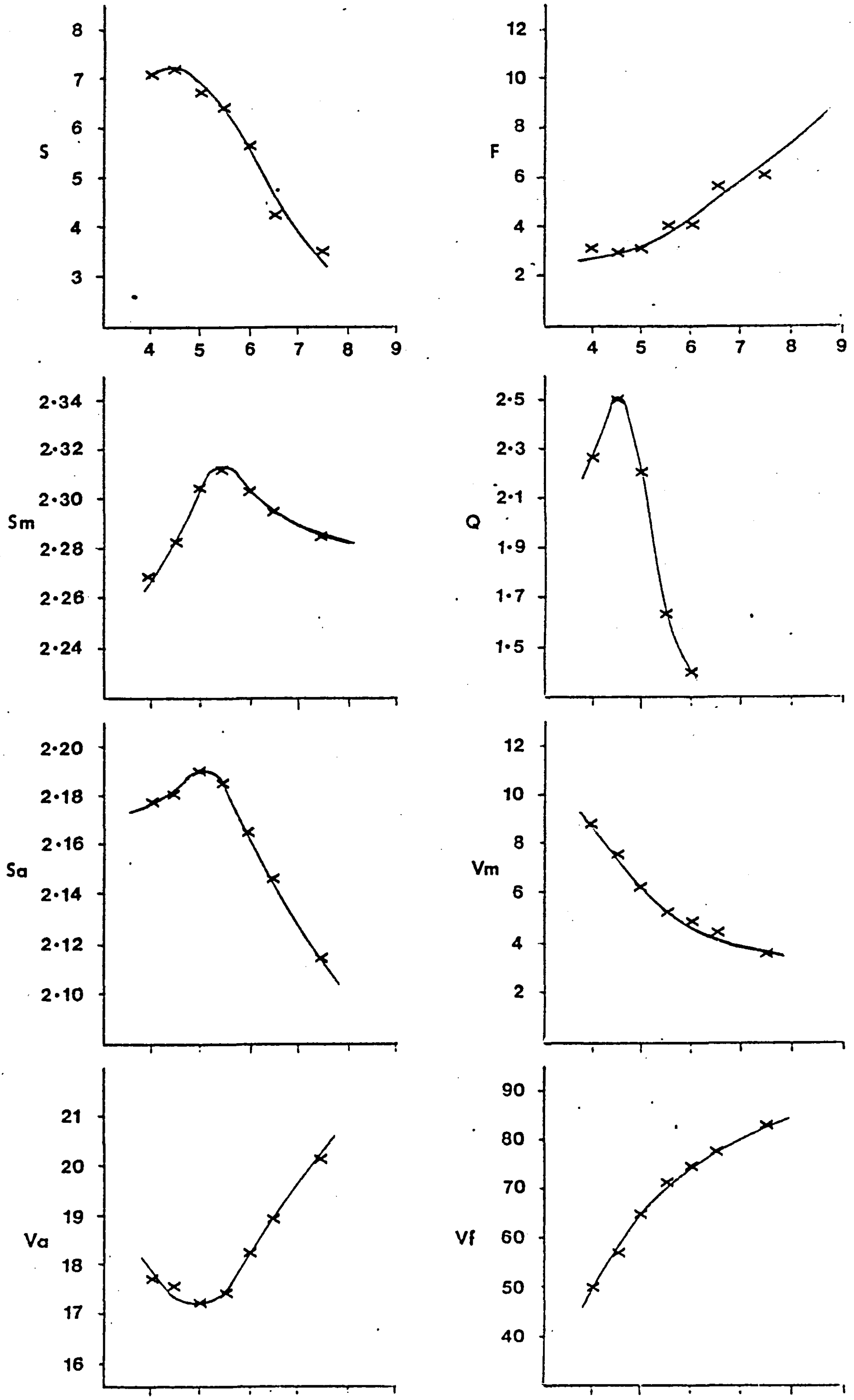


Figure D.1.8.3

Marshall Results : Sand B - 38% Stone

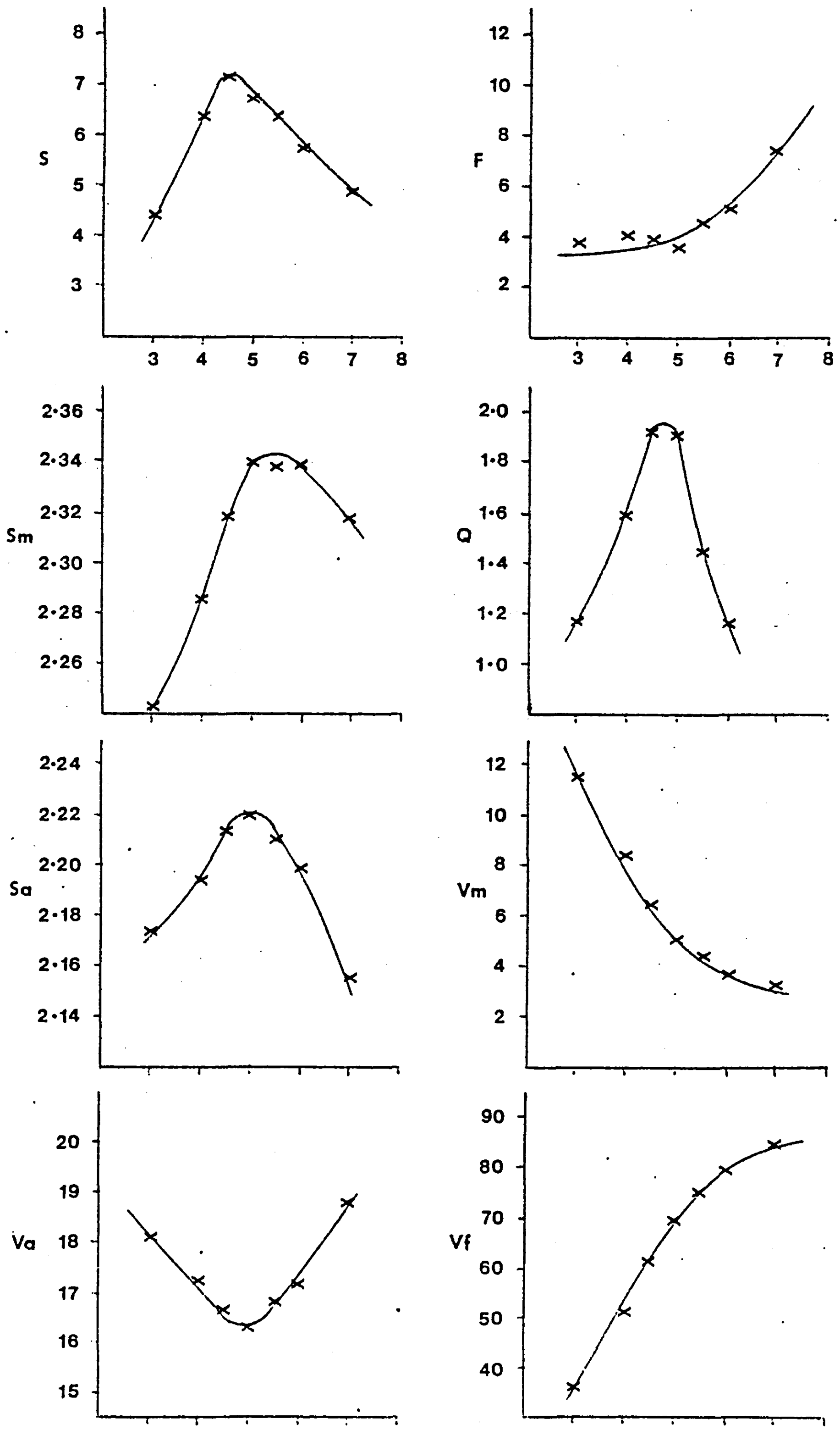
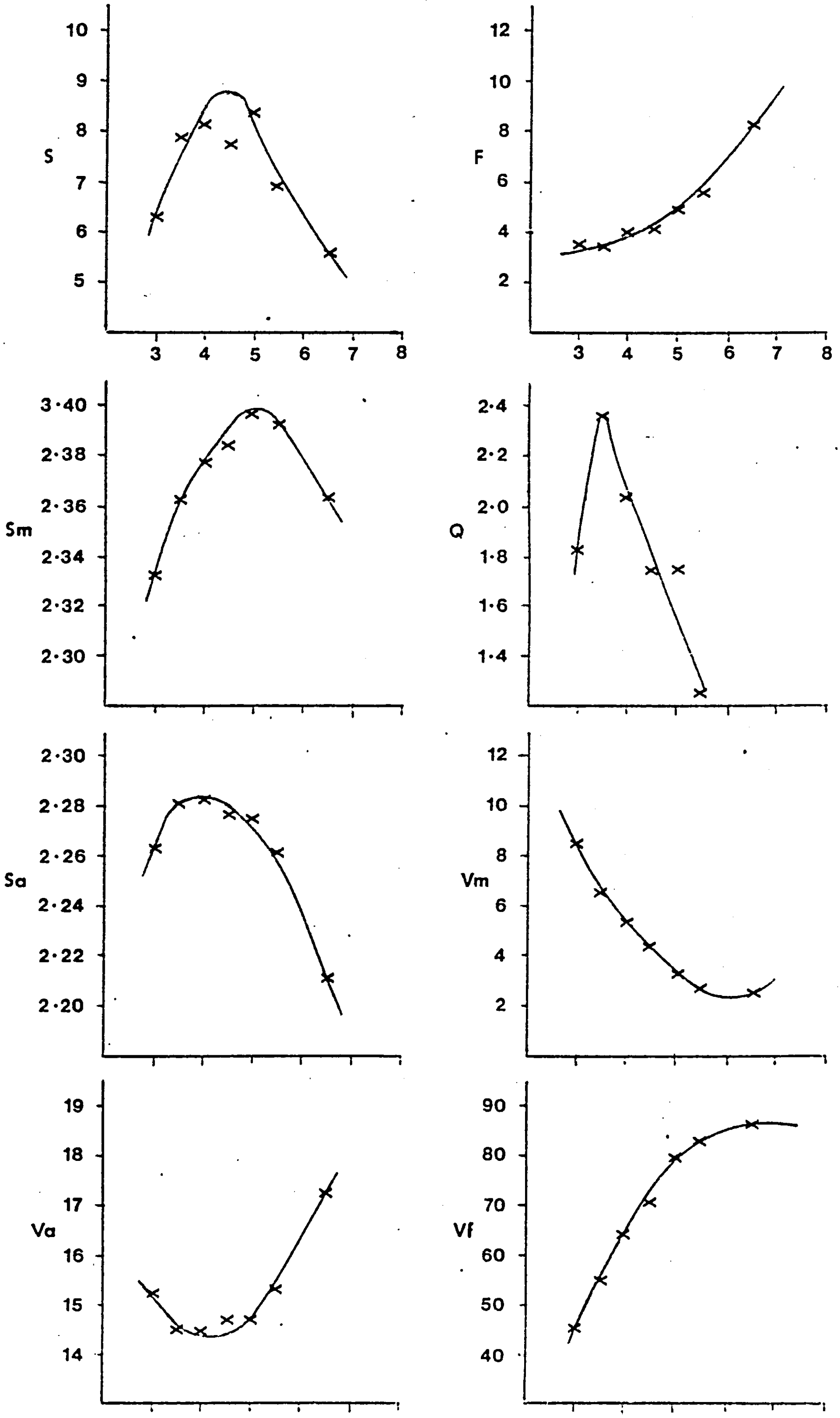


Figure D.1.8.4

Marshall Results : Sand B - 55% Stone



D.2. INDIRECT - TENSILE TEST RESULTS:

D.2.1. Introduction.

Results obtained using the Indirect-Tensile test method as described in Chapter 5 are presented in the following sections.

Tables containing results for all mixtures tested are included. The figures in tables are mean values for duplicate specimens for each mixture, in each case the mixture is identified by the MIX CODE (see 4.6.3.), the individual specimen numbers having been omitted.

The symbols at the head of each column (S_M S_A, etc.) refer to the mixture properties determined, and are defined fully under NOTATION and in Chapter 6.

For selected stone contents the tabulated results have also been presented graphically to indicate how the various properties vary with respect to binder content (w_B). Each point on the graphs represents the mean value for duplicate specimens at that binder content.

D.2.2. Tables of Results - Sand A

Table D.2.2.1. : Sand A - 0% Stone

MIX CODE	S_M	S_A	V_M	V_A	V_F	I.T.S.	$\triangle$D	T
OA9.5T	2.046	1.851	10.8	29.6	63.7	5.34	6.0	8.9
OA10.0T	2.060	1.854	9.6	29.5	67.7	5.76	5.8	9.9
OA10.5T	2.078	1.860	8.1	29.3	72.3	6.10	5.5	11.1
OA11.0T	2.096	1.866	6.7	29.1	77.0	6.30	5.7	11.1
OA11.5T	2.101	1.859	5.9	29.3	80.0	6.26	6.1	10.3
OA12.0T	2.098	1.847	5.4	29.8	82.0	6.06	6.6	9.2
OA12.5T	2.098	1.836	4.8	30.2	84.2	5.90	7.6	7.8
OA13.0T	2.090	1.818	4.5	30.9	85.4	5.52	9.4	5.9

Table D.2.2.2. : Sand A - 10% Stone

10A8.5T	2.103	1.924	9.8	27.1	64.1	5.55	4.4	12.6
10A9.5T	2.125	1.924	7.6	27.1	72.2	5.96	4.8	12.4
10A10.0T	2.131	1.918	6.7	27.4	75.7	6.28	4.9	12.8
10A10.5T	2.148	1.922	5.3	27.2	80.6	6.17	5.1	12.1
10A11.0T	2.146	1.909	4.8	27.7	82.8	6.06	5.8	10.5
10A11.5T	2.130	1.885	4.8	28.6	83.2	5.36	7.3	7.3
10A12.5T	2.094	1.838	5.5	30.4	81.9	4.77	10.5	4.5

Table D.2.2.3. : Sand A - 20% Stone

MIX CODE	S_M	S_A	V_M	V_A	V_F	I.T.S.	ΔD	T
20A7.0T	2.121	1.973	11.1	25.5	56.5	5.83	2.7	21.6
20A8.0T	2.158	1.986	8.3	25.0	67.0	6.33	3.5	18.1
20A8.5T	2.172	1.988	7.0	24.9	71.9	6.42	3.8	16.9
20A9.0T	2.184	1.988	5.9	24.9	76.6	6.87	4.1	16.8
20A9.5T	2.187	1.979	5.1	25.3	79.9	6.30	4.6	13.7
20A10.0T	2.189	1.970	4.4	25.6	82.9	5.96	5.0	11.9
20A11.0T	2.177	1.938	3.6	26.8	86.7	5.29	7.3	7.3

Table D.2.2.4. : Sand A - 30% Stone

30A6.0T	2.182	2.051	10.1	22.8	55.8	7.11	2.8	25.4
30A6.5T	2.197	2.055	8.8	22.6	61.3	7.74	2.8	27.6
30A7.0T	2.208	2.054	7.7	22.7	66.2	7.48	3.3	22.7
30A7.5T	2.228	2.060	6.2	22.4	72.4	7.62	3.2	23.8
30A8.0T	2.231	2.052	5.4	22.7	76.2	7.13	3.4	21.0
30A8.5T	2.236	2.046	4.5	23.0	80.4	6.28	4.2	15.0
30A9.0T	2.239	2.036	3.9	23.4	83.6	6.61	5.0	13.2
30A10.0T	2.219	1.997	3.3	24.8	86.7	5.31	6.6	8.1

Table D.2.2.5. : Sand A - 40% Stone

MIX CODE	S_M	S_A	V_M	V_A	V_F	I.T.S.	ΔD	T
40A5.5T	2.223	2.100	9.3	21.2	56.1	7.32	2.2	33.3
40A6.5T	2.266	2.119	6.2	20.5	69.8	8.06	2.6	31.0
40A7.0T	2.278	2.119	5.0	20.8	75.6	8.00	3.4	23.5
40A7.5T	2.287	2.116	4.0	20.6	80.8	7.53	3.3	22.8
40A8.0T	2.291	2.108	3.1	20.9	85.1	6.68	4.4	15.2
40A8.5T	2.282	2.088	2.8	21.7	86.9	6.34	5.3	12.0
40A9.5T	2.251	2.037	2.8	23.6	88.0	5.16	7.3	7.1

Table D.2.2.6. : Sand A - 55% Stone

55A3.5T	2.261	2.182	10.8	18.5	41.7	4.17	2.2	19.0
55A4.5T	2.293	2.189	8.2	18.2	55.1	7.79	3.0	26.0
55A5.0T	2.299	2.184	7.3	18.4	60.6	8.63	2.2	39.2
55A5.5T	2.329	2.200	5.4	17.8	69.9	8.38	2.6	32.2
55A6.0T	2.319	2.180	5.1	18.6	72.8	7.67	2.6	29.5
55A6.5T	2.345	2.193	3.3	18.1	81.7	7.37	2.9	25.4
55A7.5T	2.335	2.160	2.3	19.3	88.0	6.99	3.9	17.9

D.2.3 Graphical Presentation - Sand A

Figure 2.3.1

Indirect-Tensile Results : Sand A - 0% Stone

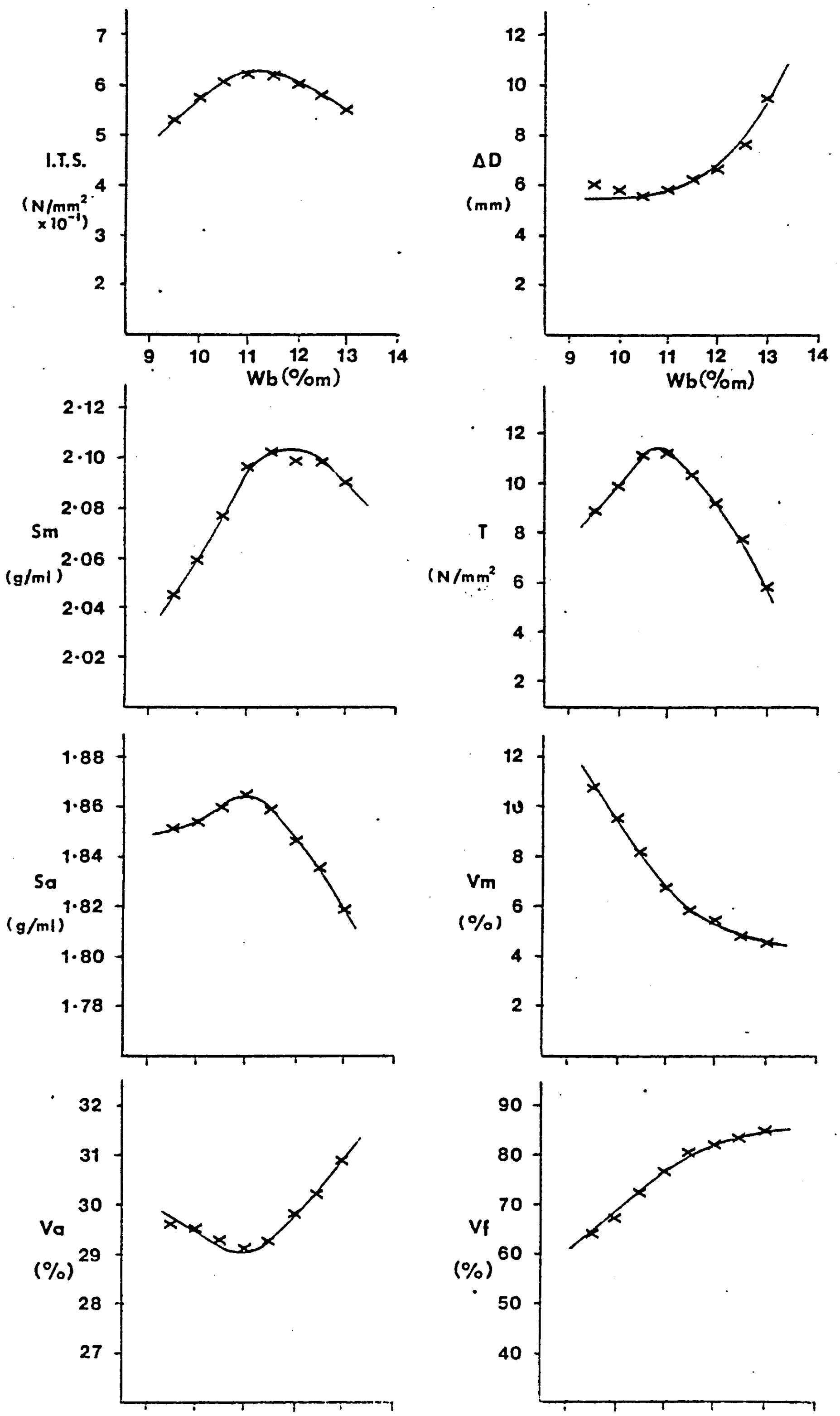


Figure 2.3.2

Indirect-Tensile Results : Sand A - 30% Stone

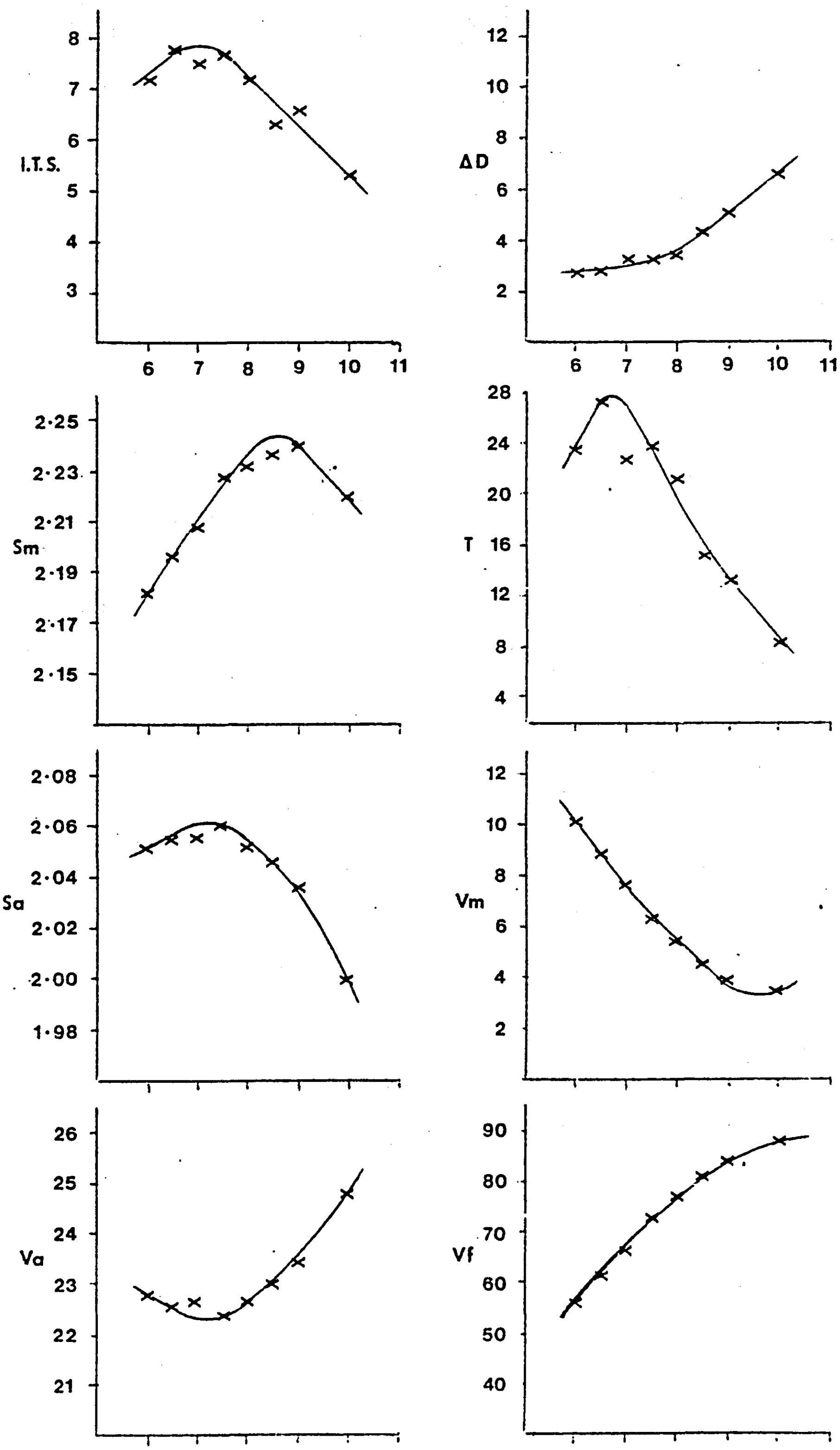


Figure 2.3.3

Indirect-Tensile Results : Sand A - 40% Stone

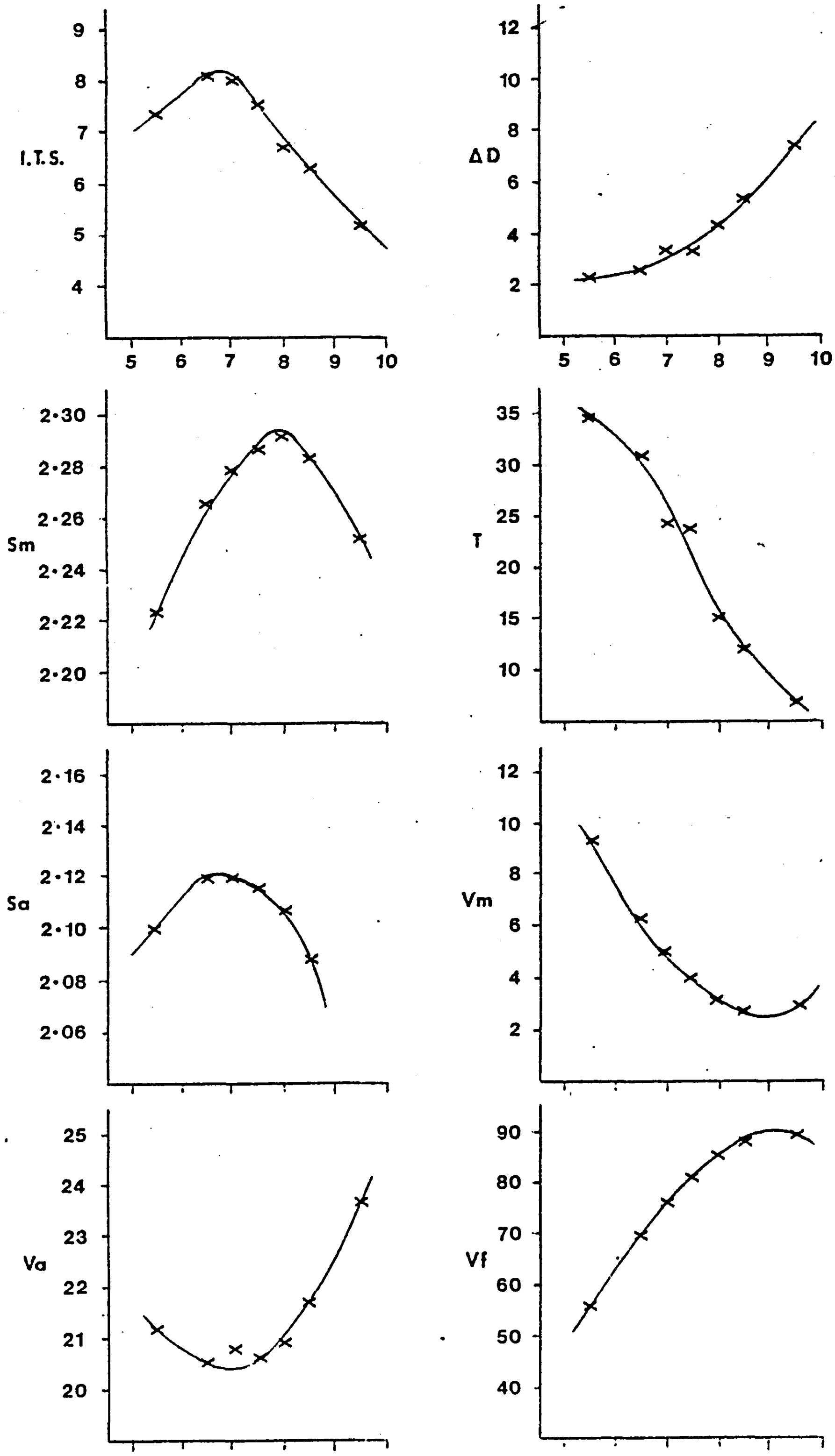
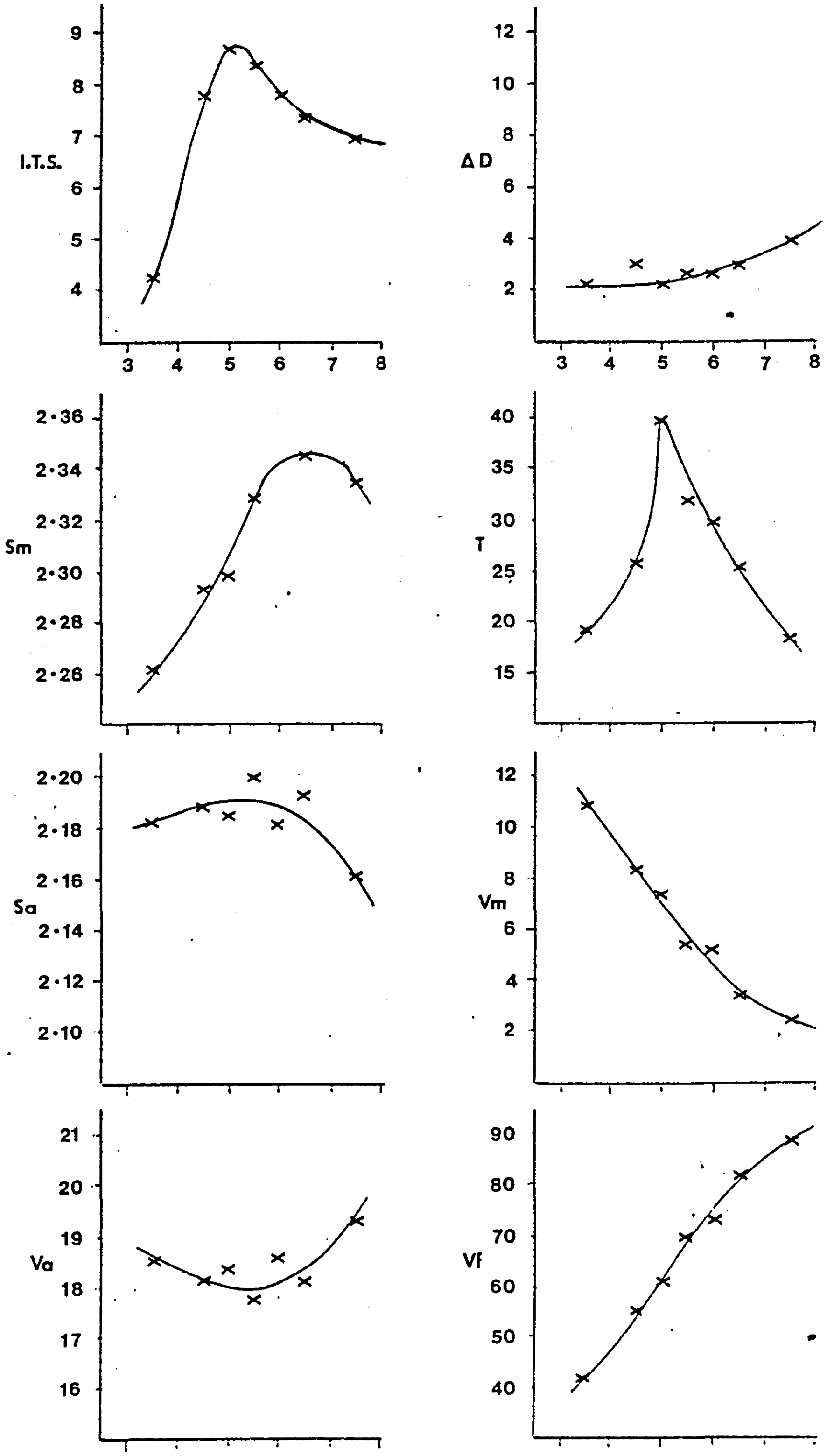


Figure 2.3.4

Indirect-Tensile Results : Sand A - 55% Stone



D.2.4 Tables of Results - Sand B.

Table D.2.4.1. : Sand B - 0% Stone

MIX CODE	S_M	S_A	V_M	V_A	V_F	I.T.S.	ΔD	T
OB5.5T	2.157	2.039	11.0	22.5	51.2	7.62	2.8	27.2
OB6.5T	2.201	2.058	7.9	21.8	63.8	8.20	3.7	22.2
OB7.0T	2.206	2.052	7.0	22.0	68.1	8.34	4.0	20.9
OB7.5T	2.218	2.052	5.9	22.0	73.4	8.24	3.7	22.3
OB8.0T	2.235	2.055	4.5	21.9	79.4	7.82	4.5	17.4
OB8.5T	2.235	2.045	3.8	22.3	82.9	7.33	4.9	15.0
OB9.0T	2.225	2.025	3.6	23.0	84.4	6.81	5.9	11.5
OB10.0T	2.192	1.973	3.7	25.0	85.1	5.85	9.1	6.4

Table D.2.4.2. : Sand B - 10% Stone

10B4.5T	2.103	2.009	14.5	23.7	38.8	4.32	1.9	22.7
10B5.5T	2.175	2.056	10.3	21.9	53.1	7.32	2.2	33.3
10B6.0T	2.200	2.068	8.6	21.4	59.9	7.85	2.4	32.7
10B6.5T	2.228	2.083	6.8	20.8	67.5	8.21	2.9	28.3
10B7.0T	2.232	2.075	6.0	21.1	71.8	7.83	2.7	29.0
10B7.5T	2.243	2.074	4.9	21.2	77.1	7.55	3.6	21.0
10B8.5T	2.231	2.042	4.0	22.4	82.3	7.24	5.2	13.9

Table D.2.4.3. : Sand B - 20% Stone

MIX CODE	S_M	S_A	V_M	V_A	V_F	I.T.S.	ΔD	T
20B4.0T	2.145	2.059	13.6	21.9	38.1	5.03	1.7	29.6
20B5.0T	2.209	2.099	9.7	20.4	52.6	7.06	2.0	35.3
20B5.5T	2.235	2.112	8.0	19.9	60.0	7.69	2.7	28.5
20B6.0T	2.259	2.124	6.3	19.5	67.7	8.24	2.6	31.7
20B6.5T	2.272	2.124	5.1	19.4	73.8	7.67	3.2	24.0
20B7.0T	2.273	2.114	4.4	19.8	78.0	7.08	3.5	20.2
20B8.0T	2.260	2.080	3.6	21.1	83.1	5.71	5.3	10.8

Table D.2.4.4. : Sand B - 30% Stone

30B4.0T	2.211	2.122	11.2	19.8	43.9	6.40	2.0	32.0
30B4.5T	2.248	2.147	9.0	18.8	52.1	7.27	2.2	33.1
30B5.0T	2.277	2.163	7.2	18.3	60.6	9.13	2.0	45.7
30B5.5T	2.297	2.170	5.7	18.0	68.2	8.96	2.2	40.7
30B6.0T	2.313	2.174	4.4	17.8	75.6	8.49	2.9	29.3
30B6.5T	2.308	2.158	3.9	18.5	78.9	7.58	3.9	19.4
30B7.0T	2.303	2.142	3.4	19.1	82.1	6.79	4.3	15.8
30B7.5T	2.290	2.118	3.3	20.0	83.5	6.23	5.1	12.2

Table D.2.4.5. : Sand B - 38% Stone

MIX CODE	S_M	S_A	V_M	V_A	V_F	I.T.S.	ΔD	T
38B3.0T	2.238	2.171	11.7	18.2	35.9	5.91	1.9	31.1
38B4.0T	2.307	2.215	7.6	16.5	54.2	8.84	1.9	46.5
38B4.5T	2.323	2.218	6.3	16.4	61.9	9.40	1.9	49.5
38B5.0T	2.336	2.221	5.0	16.3	69.6	8.36	2.2	38.0
38B5.5T	2.352	2.223	3.7	16.7	77.3	8.09	1.9	42.6
38B6.0T	2.345	2.204	3.3	17.0	80.6	7.04	2.9	24.3
38B7.0T	2.319	2.157	3.0	18.8	84.0	5.21	4.0	13.0

Table D.2.4.6. : Sand B - 55% Stone

55B3.0T	2.337	2.267	8.3	15.1	45.2	5.64	1.5	37.6
55B3.5T	2.368	2.285	6.4	14.4	55.6	8.46	1.9	44.5
55B4.0T	2.387	2.292	4.9	14.2	65.5	9.99	1.8	55.5
55B4.5T	2.396	2.288	3.8	14.3	73.3	9.52	2.3	41.4
55B5.0T	2.399	2.279	3.0	14.7	79.4	8.32	2.9	28.7
55B5.5T	2.394	2.263	2.5	15.3	83.7	7.71	3.2	24.1

D.2.5 Graphical Presentation - Sand B

Figure 2.5.1

Indirect-Tensile Results : Sand B - 0% Stone

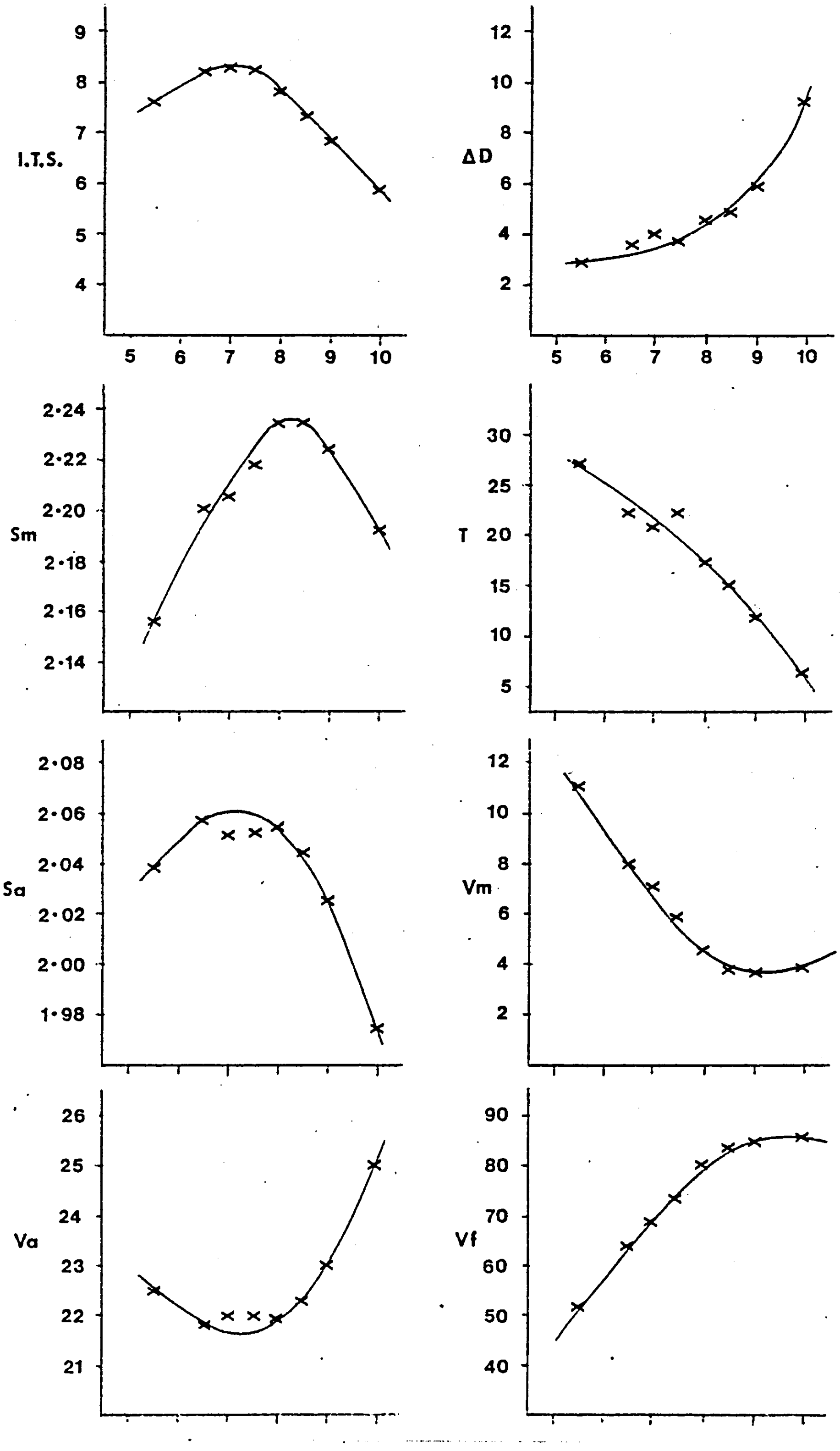


Figure 2.5.2

Indirect-Tensile Results : Sand B - 30% Stone

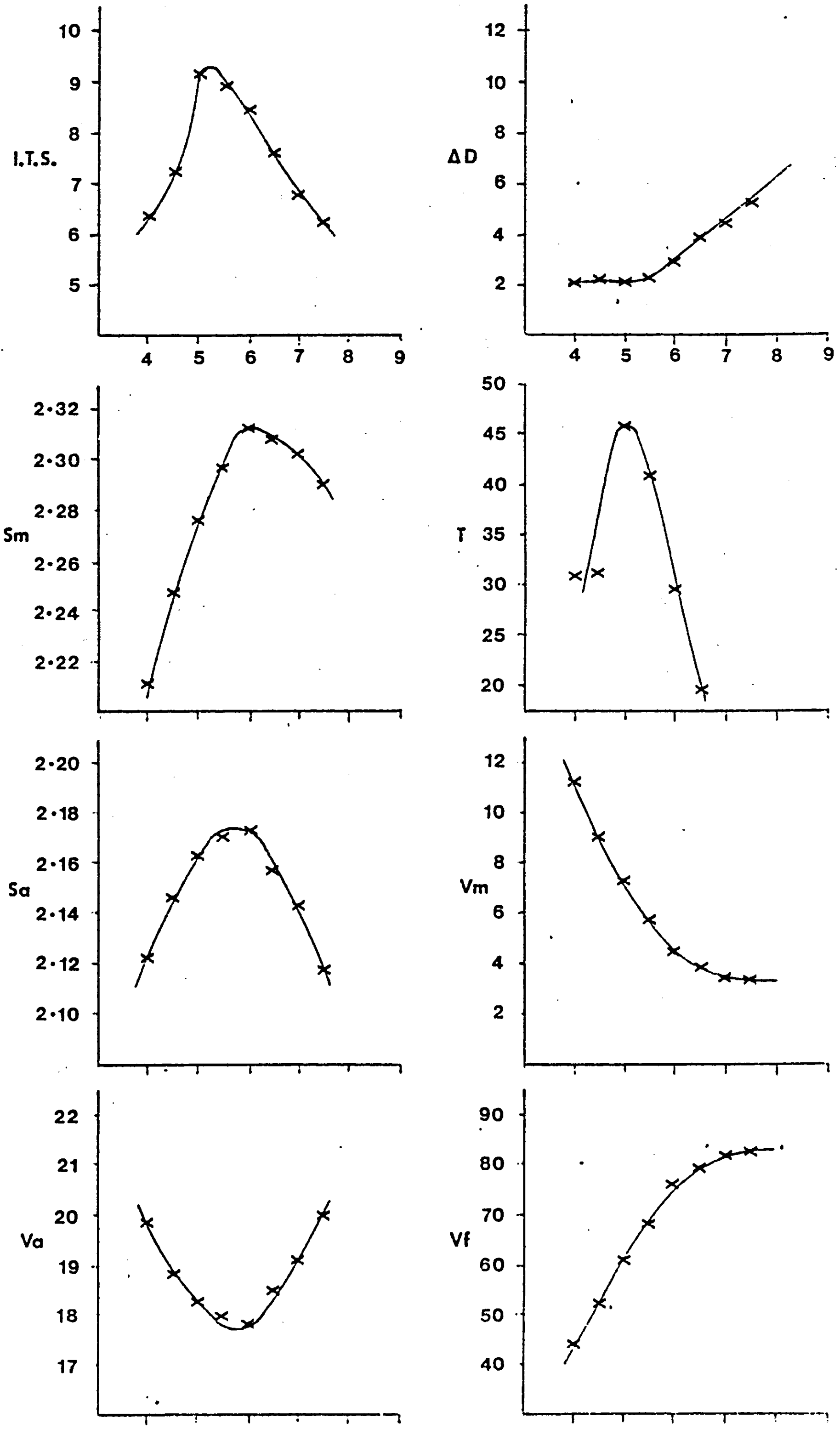


Figure 2.5.3

Indirect-Tensile Results : Sand B - 38% Stone

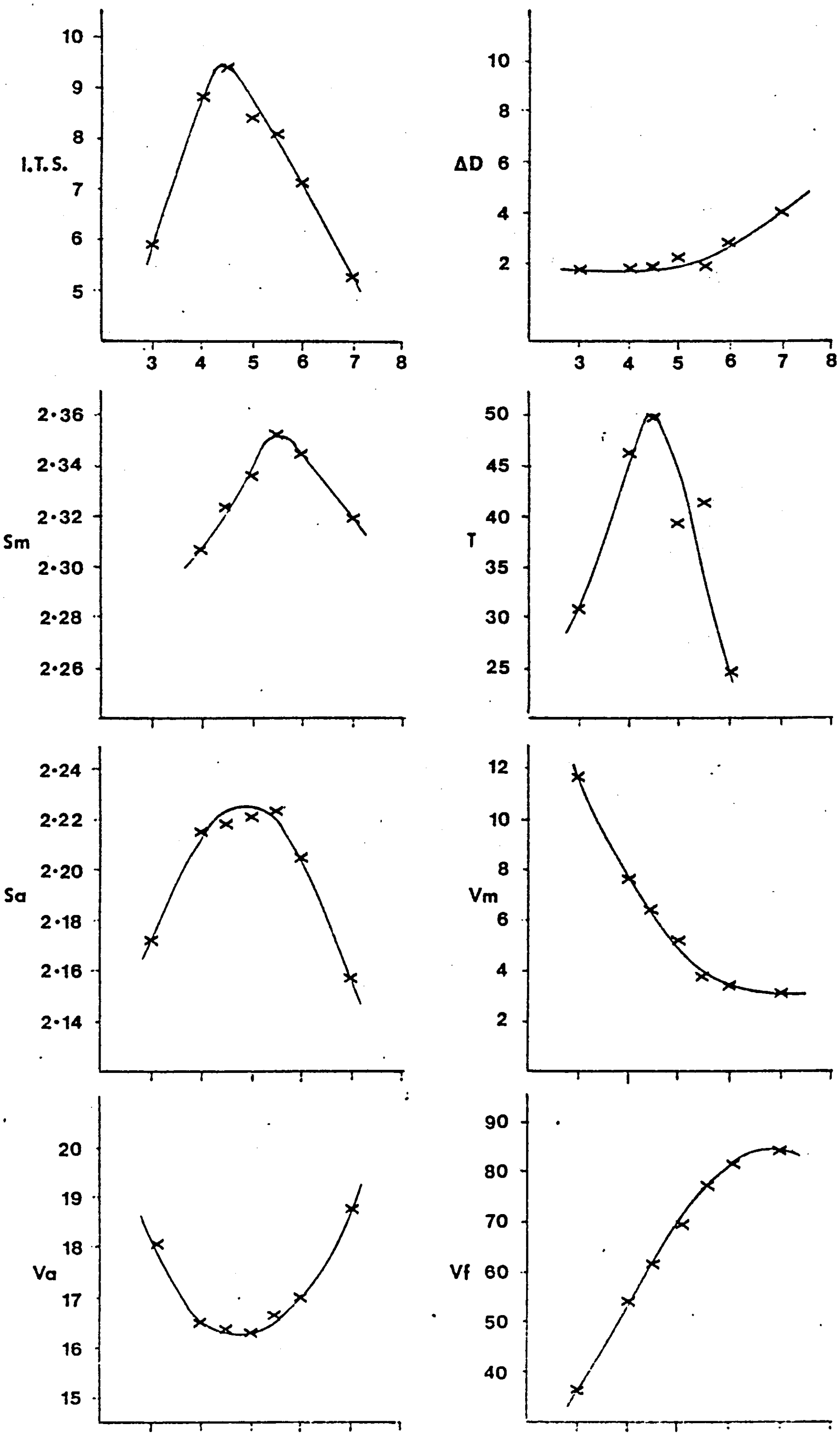
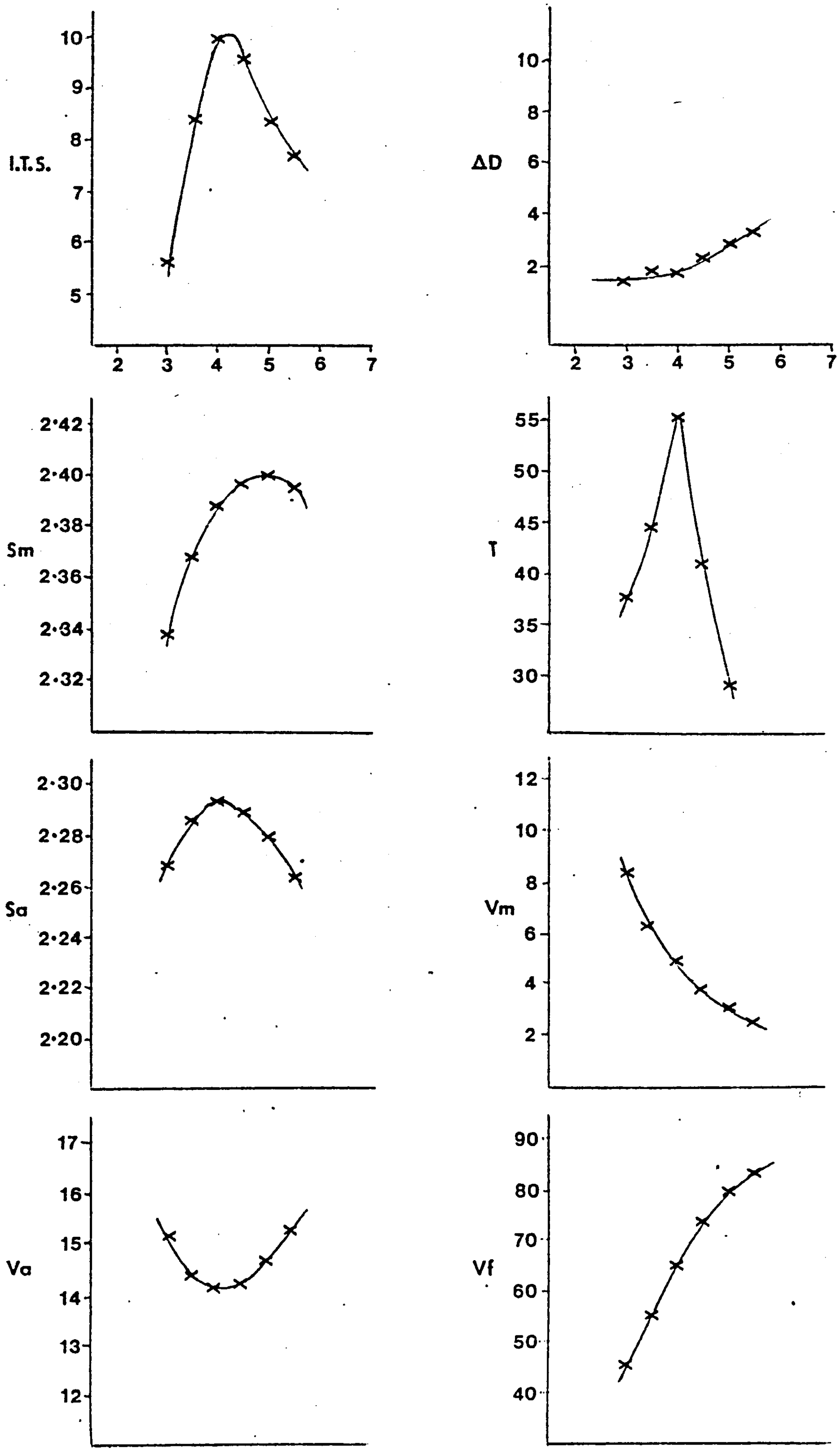


Figure 2.5.4

Indirect-Tensile Results : Sand B - 55% Stone



D.3. WHEEL-TRACKING TEST RESULTS

D.3.1. Introduction:

Results obtained using the Wheel-Tracking test method, as described in Chapter 5 are presented in the following sections.

Tables containing results for all mixtures tested are included. The figures given in the tables are the values obtained for tests on a single specimen of each mixture. In each case the mixture can be identified by the specimen identification number (see 4.6.3).

The symbols at the head of each column (S_M, S_A, etc.) refer to the mixture properties determined, and are defined fully under NOTATION and in Chapter 6.

For each of the Stone Contents tested the tabulated results have also been presented graphically to indicate how the various properties vary with respect to binder content (w_B). Each point on the graphs represents the result obtained for a single specimen at that binder content.

D.3.2. Table of Results - Sand A

Table D.3.2.1. : Sand A - 30% Stone (Series No. 1)

SPECIMEN I.D.	S_M	S_A	V_M	V_A	V_F	T.R.
30A6.0W1	2.064	1.940	15.3	27.3	44.0	2.0
30A6.5W1	2.101	1.964	13.2	26.5	50.0	1.4
30A7.0W1	2.126	1.977	11.5	26.0	55.6	2.8
30A7.5W1	2.171	2.008	9.0	24.8	63.7	2.3
30A8.0W1	2.198	2.022	7.2	24.3	70.3	2.4
30A8.5W1	2.209	2.021	6.1	24.9	73.2	1.9
30A9.0W1	2.210	2.011	5.4	24.7	78.2	3.2
30A10.0W1	2.217	1.995	3.8	25.3	85.1	8.1
30A11.0W1	2.192	1.951	3.6	27.0	86.7	22.5

Table D.3.2.2. : Sand A - 30% Stone (Series No. 2)

30A6.0W2	2.053	1.930	15.8	27.8	43.0	2.3
30A7.0W2	2.128	1.979	11.4	25.9	55.8	1.7
30A8.0W2	2.175	2.001	8.2	25.1	67.3	1.9
30A9.0W2	2.212	2.013	5.4	24.7	78.3	2.5
30A10.0W2	2.223	2.001	3.6	25.2	85.7	9.6
30A11.0W2	2.186	1.946	3.9	27.3	85.5	26.3

Table D.3.2.3. : Sand A - 40% Stone

SPECIMEN I.D.	S_M	S_A	V_M	V_A	V_F	T.R.
40A5.5W1	2.122	2.005	13.4	24.7	45.9	1.2
40A6.5W1	2.186	2.044	9.5	23.3	59.2	1.1
40A7.0W1	2.206	2.052	8.0	23.0	65.2	0.9
40A7.5W1	2.227	2.060	6.5	22.7	71.4	1.3
40A8.0W1	2.258	2.077	4.5	22.0	79.7	1.8
40A8.5W1	2.262	2.070	3.7	22.4	83.3	2.7
40A9.5W1	2.249	2.035	2.9	23.6	87.9	7.5

Table D.3.2.4. : Sand A - 55% Stone

55A3.5W1	2.133	2.058	15.8	23.1	31.4	0.7
55A4.5W1	2.176	2.078	12.8	22.3	42.6	0.7
55A5.0W1	2.223	2.112	10.3	21.1	51.1	1.0
55A5.5W1	2.253	2.129	8.4	20.4	59.0	1.1
55A6.0W1	2.281	2.144	6.6	20.0	66.4	1.4
55A6.5W1	2.308	2.158	4.8	19.4	75.1	1.2
55A7.5W1	2.320	2.146	3.0	19.9	84.9	3.3
55A8.0W1	2.315	2.130	2.4	20.4	88.1	5.0

D.3.3 Graphical Presentation - Sand A

Figure D.3.3.1

Wheel Tracking Results : Sand A - 30% Stone

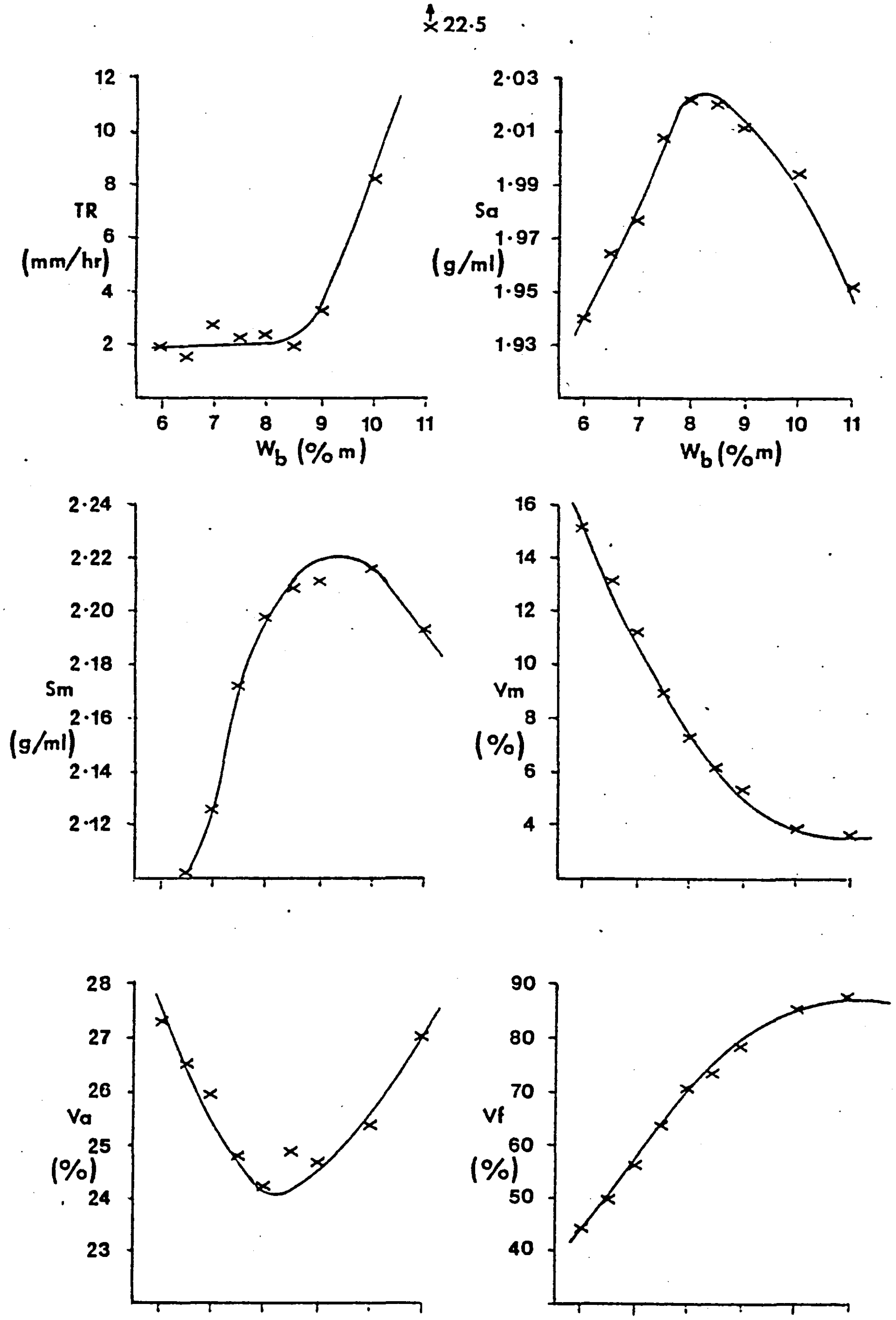


Figure D.3.3.2

Wheel Tracking Results : Sand A - 40% Stone

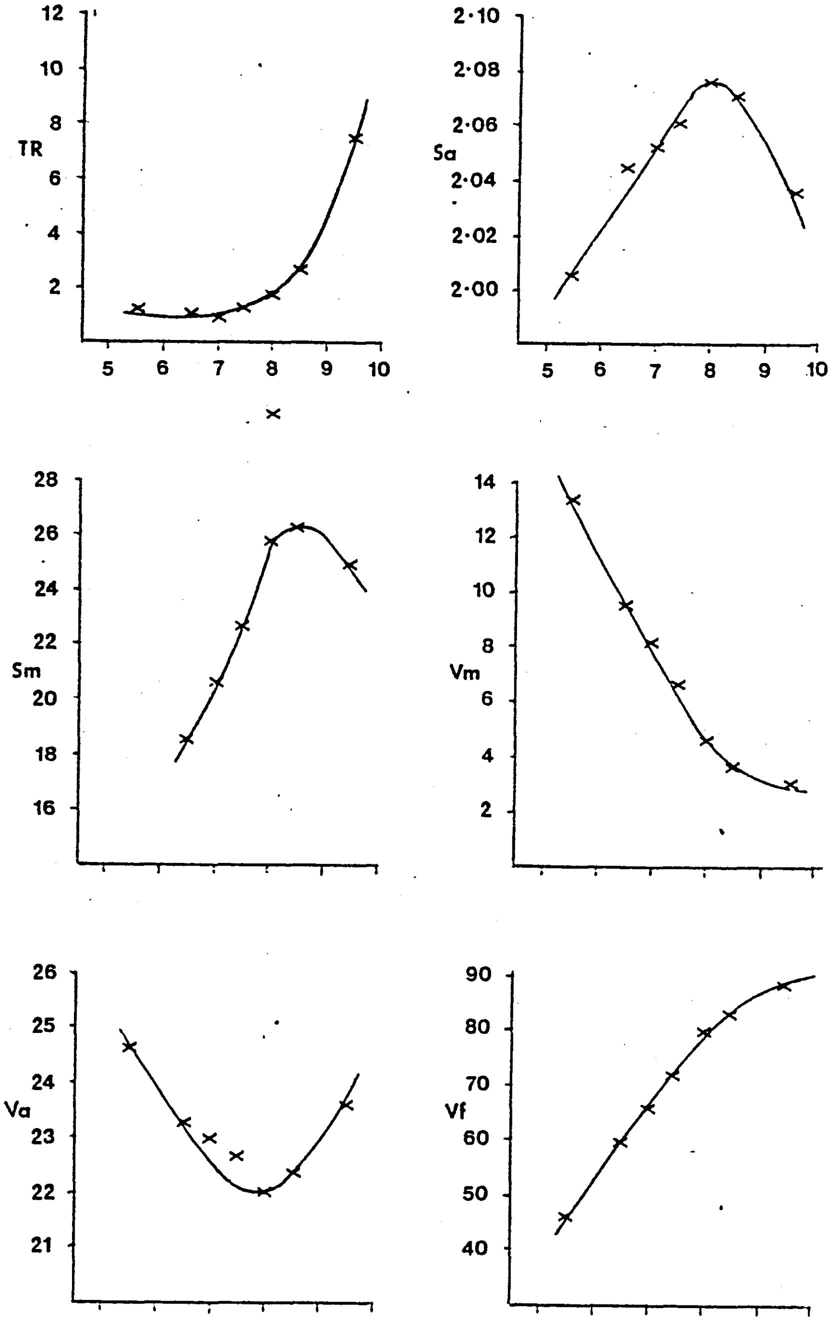
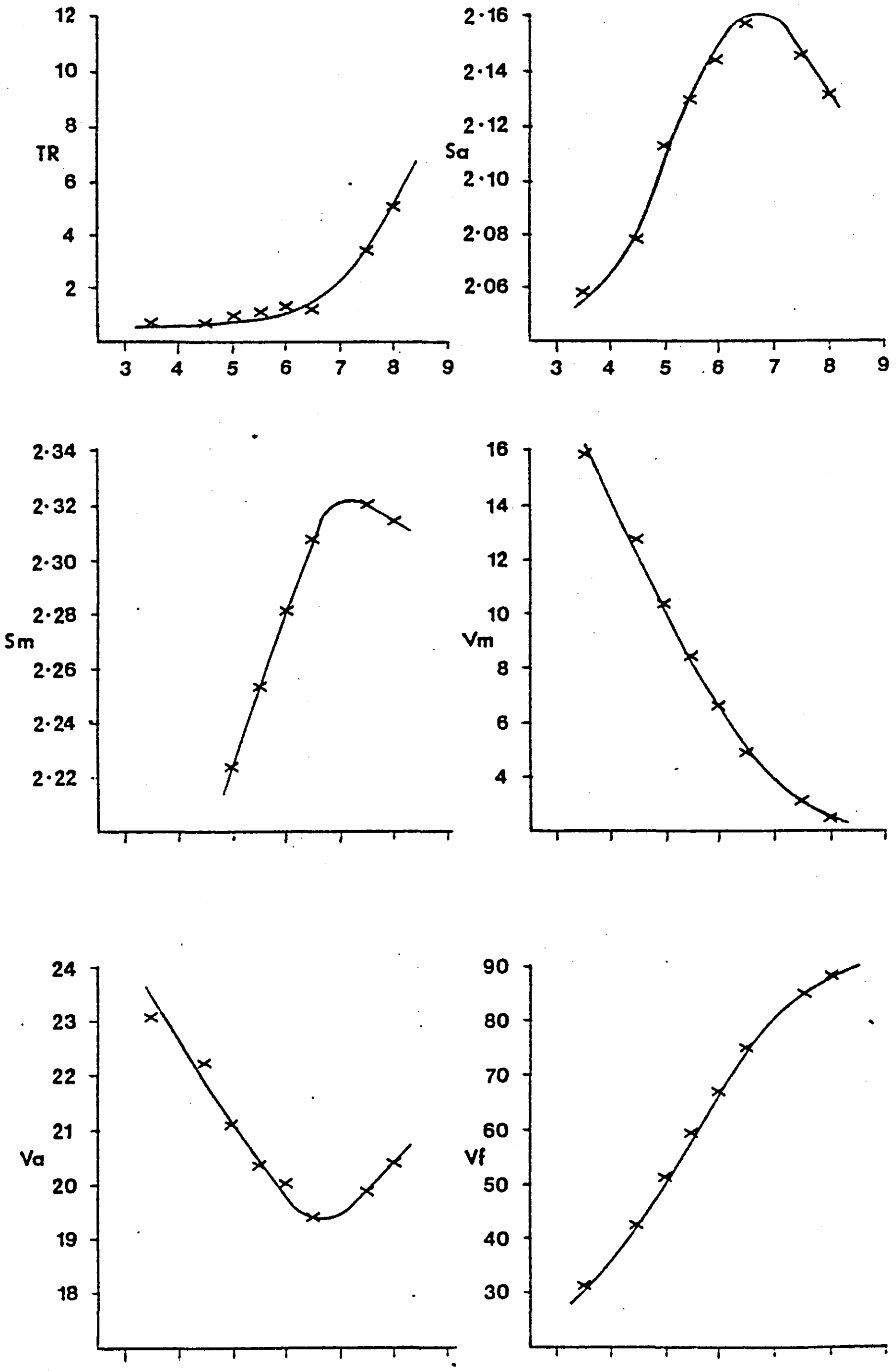


Figure D.3.3.3

Wheel Tracking Results : Sand A - 55% Stone



D.3.4. Tables of Results - Sand B.

Table D.3.4.1. : Sand B - 30% Stone

SPECIMEN I.D.	S_M	S_A	V_M	V_A	V_F	T.R.
30B4.0W1	2.123	2.038	14.7	23.0	35.9	0.9
30B4.5W1	2.177	2.079	11.9	22.0	43.2	1.7
30B5.0W1	2.201	2.091	10.3	21.0	50.9	2.3
30B5.5W1	2.228	2.106	8.5	20.4	58.3	2.7
30B6.0W1	2.256	2.121	6.7	19.8	66.4	3.0
30B6.5W1	2.287	2.138	4.8	19.2	75.2	3.3
30B7.0W1	2.284	2.124	4.2	19.7	78.8	5.6
30B7.5W1	2.276	2.105	3.9	20.5	80.8	7.5

Table D.3.4.2. : Sand B - 38% Stone

38B4.0W1	2.181	2.094	12.6	21.1	40.1	1.7
38B4.5W1	2.231	2.131	10.0	19.8	49.2	0.8
38B5.0W1	2.252	2.139	8.5	19.4	56.4	1.9
38B5.5W1	2.290	2.164	6.2	18.4	66.5	1.9
38B6.0W1	2.321	2.182	4.3	17.8	76.0	2.1
38B6.5W1	2.321	2.170	3.6	18.3	80.0	5.0
38B7.0W1	2.318	2.156	3.0	18.8	83.8	10.9

Table D.3.4.3. : Sand B - 55% Stone

SPECIMEN I.D.	S_M	S_A	V_M	V_A	V_F	T.R.
55B3.0W1	2.236	2.169	12.2	18.7	34.8	1.3
55B3.5W1	2.274	2.194	10.1	17.8	43.4	1.7
55B4.0W1	2.310	2.218	8.0	17.0	52.8	1.5
55B4.5W1	2.339	2.234	6.1	16.3	62.7	1.7
55B5.0W1	2.361	2.243	4.5	16.0	71.6	1.7
55B5.5W1	2.375	2.244	3.3	16.0	79.3	1.9
55B6.0W1	2.379	2.236	2.4	16.3	85.0	5.0
55B6.5W1	2.366	2.212	2.2	17.1	87.3	7.5

D.3.5 Graphical Presentation - Sand B

Figure D.3.5.1

Wheel Tracking Results : Sand B - 30% Stone

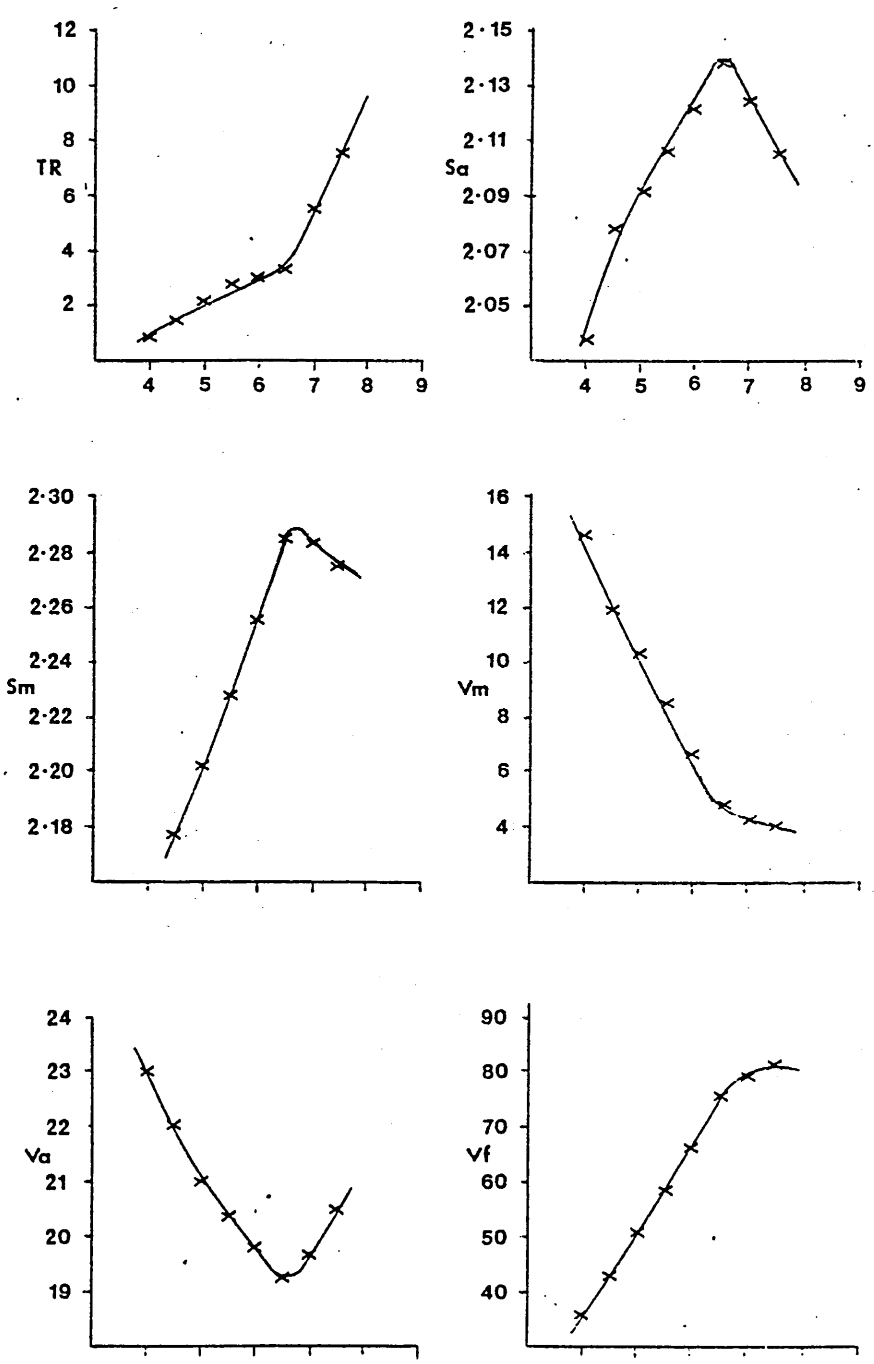


Figure D.3.5.2

Wheel Tracking Results : Sand B - 38% Stone

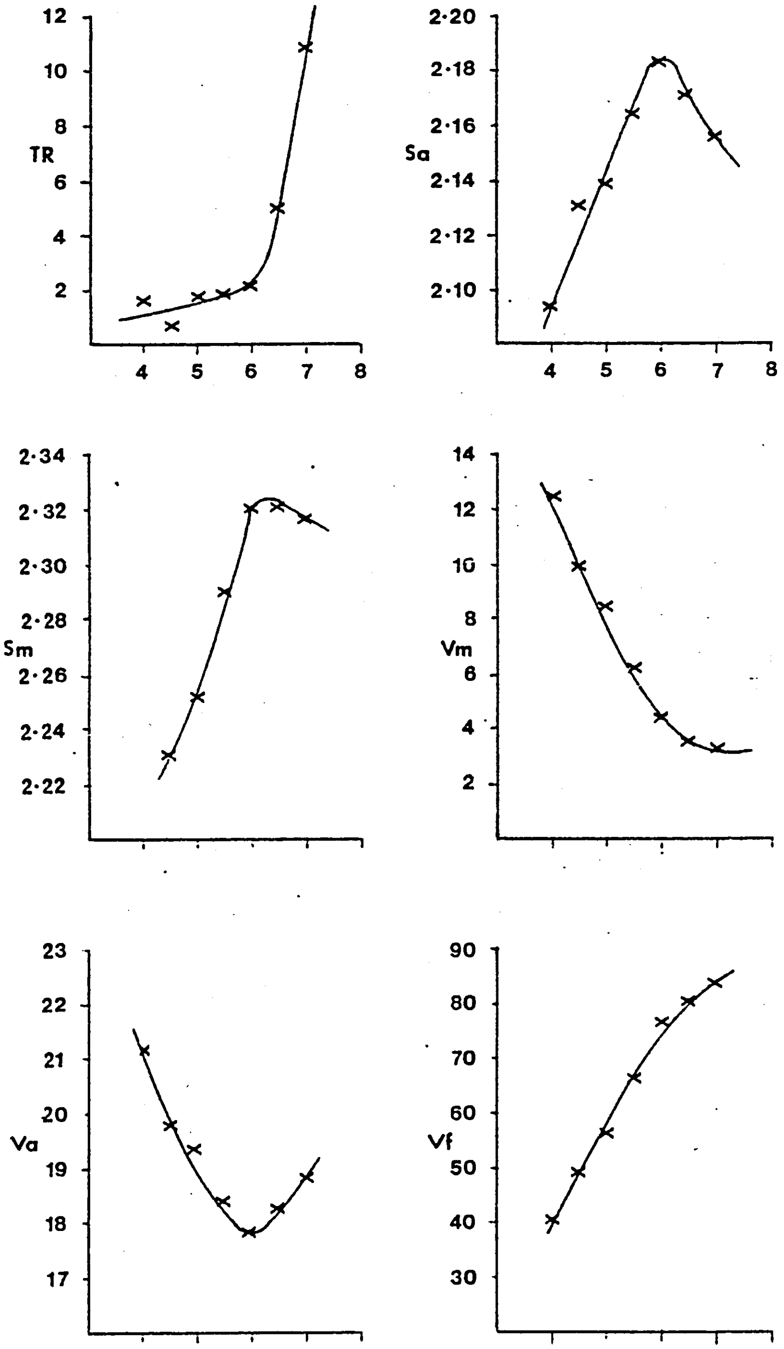
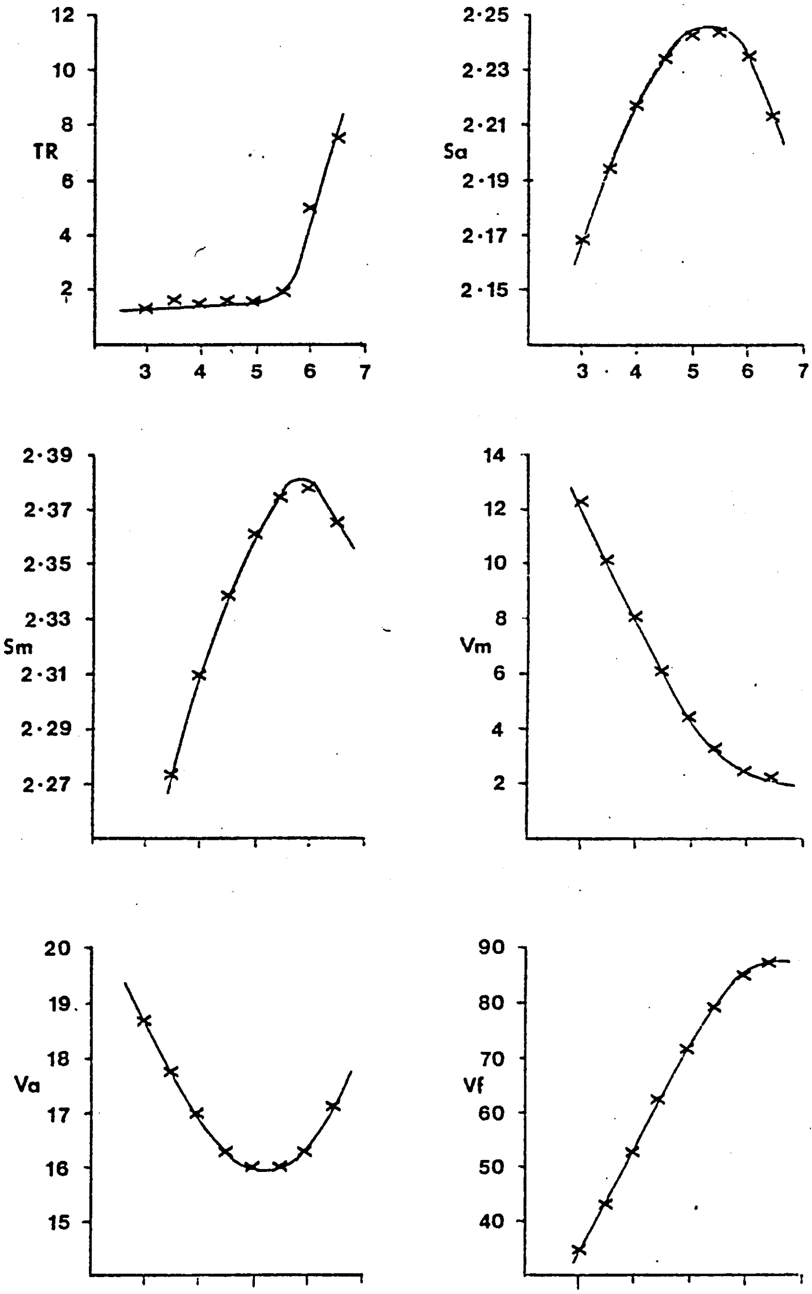


Figure D.3.5.3

Wheel Tracking Results : Sand B - 55% Stone



D.3.6. Tables of Results - Sand A; Rut-Depth Data

Table D.3.6.1. : Sand A - 30% Stone (Series No. 1).

SPECIMEN I.D.	R.D.$_{100}$	R.D.$_{1000}$	R.D.$_{END}$
30A6.0W1	0.75	1.90	2.60
30A6.5W1	0.65	1.60	2.15
30A7.0W1	0.65	2.20	3.00
30A7.5W1	0.60	1.90	2.65
30A8.0W1	0.85	2.50	3.25
30A8.5W1	1.00	2.85	3.55
30A9.0W1	0.90	2.70	3.50
30A10.0W1	2.05	6.30	8.40
30A11.0W1	6.75	-	-

Table D.3.6.2. : Sand A - 30% Stone (Series No. 2).

30A6.0W2	0.65	1.70	2.35
30A7.0W2	1.00	2.30	2.85
30A8.0W2	1.50	3.00	3.60
30A9.0W2	1.05	2.60	3.30
30A10.0W2	3.75	9.50	12.8
30A11.0W2	6.00	-	-

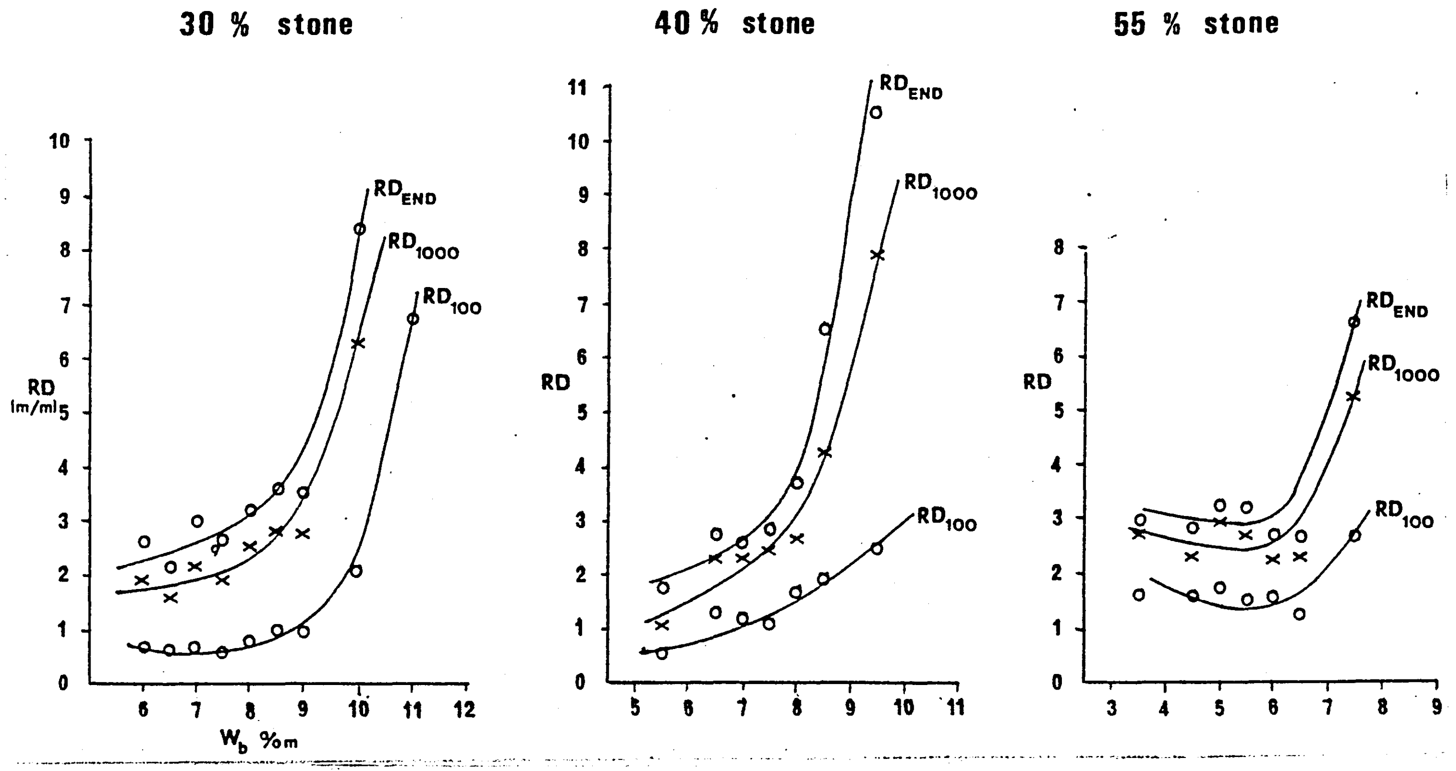
Table D.3.6.3. : Sand A - 40% Stone

SPECIMEN I.D.	R.D.$_{100}$	R.D.$_{1000}$	R.D.$_{END}$
40A5.5W1	0.55	1.05	1.70
40A6.5W1	1.35	2.30	2.70
40A7.0W1	1.20	2.30	2.55
40A7.5W1	1.05	2.45	2.85
40A8.0W1	1.65	3.10	3.65
40A8.5W1	1.90	4.25	6.50
40A9.5W1	2.45	7.90	10.50

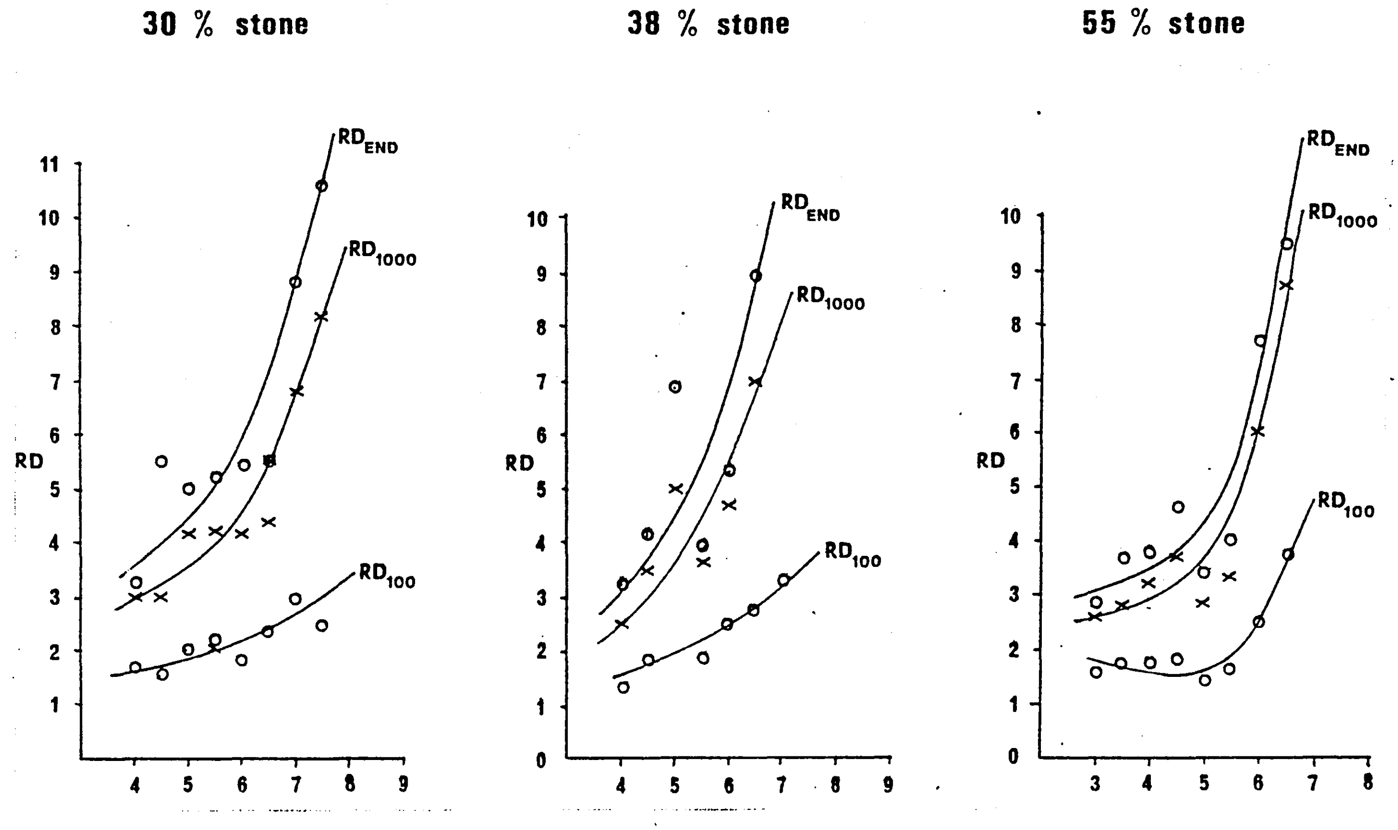
Table D.3.6.4. : Sand A - 55% Stone

55A3.5W1	1.60	2.70	2.95
55A4.5W1	1.65	2.30	2.80
55A5.0W1	1.75	2.95	3.25
55A5.5W1	1.50	2.70	3.20
55A6.0W1	1.55	2.20	2.60
55A6.5W1	1.20	2.20	2.60
55A7.5W1	2.70	5.25	6.60

D.3.7 Graphical Presentation - Sand A, Rut Depth Data



D.3.9 Graphical Presentation - Sand B, Rut Depth Data



D.3.8. Tables of Results - Sand B; Rut-Depth Data.

Table D.3.8.1. : Sand B - 30% Stone

SPECIMEN I.D.	R.D.$_{100}$	R.D.$_{1000}$	R.D.$_{END}$
30B4.0W1	1.75	3.00	3.20
30B4.5W1	1.60	3.00	5.50
30B5.0W1	2.05	4.20	5.00
30B5.5W1	2.20	4.25	5.25
30B6.0W1	1.80	4.15	5.40
30B6.5W1	2.30	4.35	5.50
30B7.0W1	3.00	6.85	8.85
30B7.5W1	2.45	8.15	10.60

Table D.3.8.2. : Sand B - 38% Stone

38B4.0W1	1.40	2.50	3.25
38B4.5W1	1.85	3.50	4.15
38B5.0W1	2.70	5.00	6.90
38B5.5W1	1.90	3.60	3.85
38B6.0W1	2.50	4.65	5.40
38B6.5W1	2.80	7.00	8.90
38B7.0W1	3.30	11.75	15.70

Table D.3.8.3. : Sand B - 55% Stone

SPECIMEN I.D.	R.D.$_{100}$	R.D.$_{1000}$	R.D.$_{END}$
55B3.0W1	1.60	2.60	2.80
55B3.5W1	1.75	2.80	3.65
55B4.0W1	1.75	3.25	3.80
55B4.5W1	1.80	3.70	4.60
55B5.0W1	1.40	2.80	3.40
55B5.5W1	1.60	3.25	4.00
55B6.0W1	2.50	6.00	7.75
55B6.5W1	3.75	8.75	9.50

E. STATISTICAL METHODS

E.1 Introduction

The statistical terms and methods referred to during the "Discussion of Experimental Results" and elsewhere, are defined and outlined in the following sections. In each case, descriptions have been kept to a minimum and for a more detailed explanation of the terms and the underlying theory, the reader is referred elsewhere.(205)(206)

E.2 Characteristics of Dispersions

E.2.1 Arithmetic Mean

This was used to give a typical representation of a group of observations taken as a whole, and to describe the value about which the observed values clustered.

$$\text{Arithmetic Mean } (\bar{x}) = \frac{1}{n} \sum_{i=1}^{n} x_i$$

where

x_i = an observed value

n = total number of observations

E.2.2 Variance and Standard Deviation

These parameters were used to measure the degree of dispersion (scatter) of the observed values about the mean.

$$\text{Variance } (S^2) = \frac{1}{n-1} \sum_{i=1}^{n} (x_i - \bar{x})^2$$

where

x_i = an observed value

n = total number of observations

$\bar{x}$ = sample mean

$$\text{Standard Deviation (S)} = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (x_i - \bar{x})^2}$$

N.B. Standard Deviation is expressed in the same units as the variate (x).

E.2.3 Coefficient of Variation

Used to express the dispersion (scatter) of the observed values, as a percentage of the sample mean.

$$\text{Coefficient of Variation (V)} = \frac{S}{\bar{x}} \times 100 \quad (\%)$$

where

$\bar{x}$ = sample mean

S = sample standard deviation

E.2.4 Range

Provided the simplest measure of dispersion of the observed values, and was merely the difference between the highest and lowest observations.

E.3 Accuracy of the Mean

To measure the degree of precision that could be expected of the mean, of a single sample, the Standard Deviation of the Mean was calculated, and was referred to as the Standard Error of the Mean.

$$\text{Standard Error of the Mean } (S_{\bar{x}}) = \frac{S}{\sqrt{n}}$$

where

S = sample standard deviation

n = total number of observations (sample size).

E.4 Comparison of Means

The means of two samples ($\bar{x}_1$ and $\bar{x}_2$) were compared for the purpose of determining whether the observed difference $|\bar{x}_1 - \bar{x}_2|$ was due to chance only, or whether some real cause should be suspected to be responsible and hence consider the difference to be statistically significant.

E.4.1 The t-Test

This test was applied to the null-hypothesis that the two samples being compared were drawn from the same population, and the probability that the difference $|\bar{x}_1 - \bar{x}_2|$ had a value as larger, or greater than observed, was calculated.

The significance of the difference was measured by the ratio of the difference $|\bar{x}_1 - \bar{x}_2|$ to its standard deviation (S_d), and is denoted by t

$$t = \frac{\bar{x}_1 - \bar{x}_2}{\sqrt{\dfrac{\sum(x_1 - \bar{x}_1)^2 + \sum(x_2 - \bar{x}_2)^2}{(n_1 - 1) + (n_2 - 1)} \left(\dfrac{n_1 + n_2}{n_1 n_2}\right)}}$$

where

$\bar{x}_1$ = mean of sample no. 1

$\bar{x}_2$ = mean of sample no. 2

n_1 = number of observations in sample no. 1

n_2 = number of observations in sample no. 2

x_1 = an observed value in sample no. 1

x_2 = an observed value in sample no. 2.

The probability of $\left| \bar{x}_1 - \bar{x}_2 \right|$ exceeding t S_d, if drawn by chance from the same population, represents the odds against the null hypothesis, and is known as the level of significance. Values of t, for various levels of significance and degrees of freedom $= (n_1 - 1) + (n_2 - 1)$, are tabulated.(205) If the calculated t was greater than the tabulated t at the level of significance specified, the null hypothesis was rejected and it is concluded that the difference was significant. If the calculated t was less than the tabulated t, the null hypothesis was accepted, but it was not possible to tell whether there was no difference between the means or whether the data were insufficient to establish whether or not there was a difference.

N.B. The level of significance at which the null-hypothesis was rejected was specified as 5%.

The null-hypothesis being examined by the t-test assumes that the variances of the two samples, are from the same population (not significantly different), this was checked by means of the F-test.

E.4.2 The F-Test

This was used to test if the variances of the two samples being compared are significantly different, and adopts the null-hypothesis that the variances belong to the same population. The F-value was calculated as follows:

$$F = \frac{S_1^2}{S_2^2} \qquad\qquad S_1 > S_2$$

Values of F are tabulated(205) for different levels of significance and degrees of freedom, $V_1 = n_1 - 1$ and $V_2 = n_2 - 1$. If the calculated F was greater than the tabulated F, the probability that the difference between S_1^2 and S_2^2 is due to chance was smaller than the specified probability, and the null-hypothesis was rejected and the variances were considered to be significantly different. If the calculated F was less than the tabulated F, the null-hypothesis was accepted and S_1^2 and S_2^2 were considered to be from the same population.

E.4.3 Ratio of Standard Deviations (tan θ)

Where the variances of two samples were found to be significantly different, the t-test was not applicable, and a test in which the ratio of the standard deviations of the sample means was considered in determining the significance of the difference between the means, was used.

$$\text{Ratio of sample Standard Deviations} = \frac{S_{\bar{x}_1}}{S_{\bar{x}_2}} = \tan\theta$$

The difference $|\bar{x}_1 - \bar{x}_2|$ was considered significant if

$$\frac{|\bar{x}_1 - \bar{x}_2|}{\sqrt{S_{\bar{x}_1}^2 - S_{\bar{x}_2}^2}} > d$$

Values of d are tabulated,(205) for different levels of significance, depending on θ and the number of degrees of freedom, $V_1 = n_1 - 1$ and $V_2 = n_2 - 1$.

E.5 Regression and Correlation Analysis

E.5.1 Linear Regression

When a linear relationship of the form

$$y = mx + c$$

was thought to exist between two variables x and y, the method of Least-Squares regression was used to determine the constants m and c,

$$m = \frac{n\sum xy - \sum x \sum y}{n\sum x^2 - \left(\sum x\right)^2}$$

and

$$c = \frac{\sum x^2 \; \sum y - \sum x \sum xy}{n\sum x^2 - \left(\sum x\right)^2}$$

and hence the equation of the "best fit" straight line through the data was determined.

E.5.2 Non-Linear Regression

The application of Least-Squares Regression to non-linear relationships is somewhat complex, however, it was found possible to transform the non-linear relationship into a linear one. In the case of the Power Function

$$y = ax^{-b}$$

it was possible to rectify it by taking logarithms, such that the transformed variables are linearly related

$$\log_{10}y = \log_{10}a - b \log_{10}x$$

and the constants $\log_{10}a$ and b were determined from linear regression, as in E.5.1.

E.5.3 Correlation Coefficient

The Correlation Coefficient (r) was used to express the degree of association that exists between two variables χ and y

$$r = \frac{n \sum xy - \sum x \sum y}{\sqrt{\left[n \sum x^2 - \left(\sum x\right)^2\right]\left[n \sum y^2 - \left(\sum y\right)^2\right]}}$$

The value of r must lie in the range

$$0 \leq |r| \leq 1$$

and a high value of r, indicated the existance of a close mathematical relationship between the two variables.