SOME ASPECTS OF P.F.A. IN CONCRETE

by

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SYNOPSIS

The use of pulverised fuel ash (p.f.a.) in concrete has been the subject of widespread discussion and debate in recent years. One of the principal problems of using this material is its variability in quality with respect to both source and power station load.

The object of this investigation is to assess the influence, upon the workability, strength and durability properties of concrete, using selected and unselected material from the same source.

The author also studies the interrelationships between the different testing methods used to assess workability and strength.

The content of this thesis represents a selection of the work carried out by the author between January 1973 and December 1975 in the Department of Civil Engineering and Building at Sheffield Polytechnic (now Sheffield City Polytechnic).

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1.0 Introduction

In recent years there has been increasing interest into the use of waste materials in the construction industry. The reasons for this are various although an increase in the awareness of environmental pollutants and escalating cost of traditional materials have been contributory factors.

The field of concrete technology is no exception and during the past 40 years much research has been done into the use of such materials as burnt oil shale, blastfurnace slag and pulverised fuel ash (p.f.a.) as aggregates and cement replacements in concrete.

It is with the last mentioned material (p.f.a.) and its use as a cement and fine aggregate replacement in concrete that this thesis is concerned.

Pulverised Fuel Ash (termed fly ash and cendres volantes in the U.S.A. and France respectively) is the name given to the largely amorphous siliceous residue extracted from the furnaces of coal-fired power stations and is a by-product of the electricity industry.

It is relatively cheap material (roughly equal to 1/3 of the cost of cement on a tonnage basis) but its quality can be extremely variable; depending upon both the source of supply and upon whether the power stations are operating under base or peak load conditions. The variable quality of material produced can have an adverse effect upon the performance of p.f.a. concretes in terms of their workability, strength and durability.

Two of the most important factors thought to influence p.f.a. performance in concrete are the % loss on ignition (unburnt carbonaceous residue) within the material and the % passing No. 300 sieve.

It is currently thought in some quarters that if both of these properties could be kept within certain limits then two of the biggest obstacles to the widespread use of p.f.a. in concretes could be removed.

A company called Pozzolanic Pty Ltd., of Chester who have had much experience with p.f.a. concretes in Australia have developed a process (virtually a sieving treatment) whereby the coarser particles, a large proportion of which are carbonaceous unburnt fuel, are excluded from the final product.

This ensures a consistent product whose physical characteristics and hence performance do not fluctuate, according to power station loads.

Experience has shown in Australia that cement and fine aggregate replacement with treated p.f.a. in concrete mixes, produced the most economic concretes in terms of cost and performance.

The objects of this research project are primarily threefold namely:-

i) The comparison of concretes which include the 'raw' (untreated) p.f.a. with those that include the processed (treated) p.f.a., in terms of their workability, strength and durability.

ii) The comparison of the concrete properties outlined in i) with those of the physical properties of each material.

iii) The determination of the most economic mix or range of concrete mixes incorporating each p.f.a. material which compare most favourably, in terms of performance, with a chosen control mix (containing no p.f.a.); in terms of workability, strength and durability.

Concurrently with these three main themes a comparison of the various workability and strength tests applied to the concrete was also proposed.

It must be emphasised that the nature of the project was such that parallel studies of the treated and untreated materials could only be done over a very limited period therefore no determination of comparative long term variability in performance was attempted.

In the course of this thesis the treated and untreated p.f.a. materials will be referred to as Pozzolan 1 (P 1) and Pozzolan 2 (P 2) respectively.

The research programme covered a period of approximately 2 years during which time 116 concrete mixes were investigated covering a wide range of cement and fine aggregate replacements with the chosen materials, P 1 and P 2.

2.0 Previous Work

2.1 Historical Background

The use of cementitious materials dates from at least 2,500 BC when the ancient Egyptians used non-hydraulic gypsum based mortars in buildings. The use of mortars is also referred to in Biblical Texts. (1) (2)

The earliest records of the use of hydraulic mortars or concretes is about 400 BC when the Roman architect Vitruvius records the use of 'a kind of powder which when mixed with lime and water sets hard under water'. The material to which he refers was initially found around Bali but later in more abundant quantities at Pozzuoli on the Bay of Naples in the shadow of Vesuvius. This material, a volcanic ash and others like it were later termed pozzolanas after the town of Pozzuoli. (3) (4)

The strength and durability of such pozzolanic mortars and concretes is attested to by the excellent condition of such buildings as the Coliseum in Rome and the Pont du Gard near Nimes in Southern France, and many others built with these early pozzolanas. (4)

The word 'pozzolana' as used in the remainder of this text describes a material which has no intrinsic cementitious properties but when mixed with lime and water combines to form a cementitious product. Reference to the above will be made in sub section 2.6.2 of the text.

The expertise of producing hydraulic concretes using pozzolanas lapsed into decay as the Roman Empire declined and it was not until 1756 when an Englishman John Smeaton charged with the rebuilding of Eddystone Lighthouse used a mixture of blue lias lime and volcanic ash (as a pozzolana) imported from Italy for the purpose.

Following Smeaton, work towards the development of synthetic hydraulic cements using calcined limestone and clay continued until in October 1824, Joseph Aspdin a Leeds builder took out the first patent for Portland Cement. Interest in pozzolanic materials remained however and at the beginning of the 20th century Michaelis (Germany) and Feret (France) carried out experimental work involving the addition of certain pozzolanic materials to portland cements. In Italy, the industrial production of pozzolanic cement began in 1923 (3).

Up until then use had been made only of natural pozzolanas. However, in 1937 Davis et al investigated the validity of using pulverised fuel ash (p.f.a.) as an artificial pozzolana in concrete. Further work was carried out by the Germans in 1941 (5) which was successfully applied in the field during 1942/3.

In 1944 the American Concrete Institute recommended fly ash (p.f.a.) for use in Portland cement concrete and it was used in the Hungary Horse Dam in the U.S.A. (1948) where the resulting savings were estimated at $1,675,000 at 1949 prices.(5)

In 1951 the French started producing commercially cements containing p.f.a. interground with blastfurnace slag and Portland cement clinker since when its use has spread to most of the major industrial nations. (3)

2.2 The use of P.F.A. concretes in the United Kingdom

Investigations into the above were first carried out by the Central Electricity Generating Board (C.E.G.B.) in 1954. This work subsequently led to its use in Stithians Dam (Cornwall).

Other projects where p.f.a. concretes have been used are Hawkridge Dam (Somerset), in foundation work for Ferrybridge 'C' Power Station and in dock walls for the Leith Harbour development. (6)

The above examples refer to 'mass' concrete structures where high strength concrete is not usually called for; the 28 day compressive strengths of the above examples varying from 16.5 to 30 N/mm^2. (6)

2.3 Production of P.F.A. in the United Kingdom

In 1969 approximately 80% of electricity was produced from pulverised coal but by 1973 this had dropped to 75%. (7) With the advent of nuclear energy and oil fired power stations this proportion is expected to drop still further. Nevertheless coal is likely to provide a considerable proportion of our power requirements until the end of this century and as the present proportion of p.f.a. used for concrete still remains small there is likely to be considerable scope for the future use of p.f.a. in concrete. (7)

In 1969 the annual production of p.f.a. was 10 million tonnes of which 3.6 million tonnes were used in the construction industry as follows:-

Table 2.3 Utilisation of P.F.A. (7)

Constructional purpose	Tonnes p.a.
Structural Fill	2.0 m
Block and brick manufacture	1.1 m
Lightweight aggregate	0.2 m
Cements	0.2 m
Other	0.1 m
Total	3.6 m

Several older stoker fired power stations work for a large percentage of their time under fluctuating load conditions and in doing so produce p.f.a. of varying chemical and physical composition. This variability has discouraged the use of p.f.a. as a concrete material. These are however being replaced by more modern stations such as Ferrybridge 'C', Didcot, Drax, Fiddlers' Ferry 'B' etc which produce a more consistent p.f.a. grading;more suitable for use as a cement replacement compound.

2.4 Factors influencing the use of P.F.A. in concrete

At this stage it would be useful to summarise the factors influencing the use of p.f.a. in concrete. These are listed as follows:-

1) Geographical Location - position of source relative to that of utilisation i.e. transport costs.
2) Availability - adequate supplies for the work in hand.
3) Quality of product - in terms of average composition and variability.
4) Relative cost of alternative materials.
5) Conservation - reduction in demand for energy, land use and other materials e.g. cement.
6) Performance - in terms of p.f.a. concrete properties compared with that of alternative concretes.
7) Market - size, research and penetration.
8) Conservatism - static and dynamic; indicated by reluctance of industries for various reasons to utilise new products.

It is difficult to sum up the above in two words but if one puts the engineer in the role of the consumer choosing a product he is principally interested in two things namely a) Cost and b) Performance. Since he is not in a vacuum, both of these will be considered in the light of available alternatives (principally cement and fine aggregate in this case) before he makes a choice.

2.5 Recent Research into P.F.A. as a Concrete constituent material.

2.5.1 Introduction

The following is an account of the research carried out during the post war years principally in France, United Kingdom and the United States and is a representative selection of the work done by individuals on behalf of such institutions as the following:-

Organisation	Country
British Coal Utilisation Council (B.C.U.C.)	United Kingdom
Cement and Concrete Association (C. & C.A.)	United Kingdom
Central Electricity Generating Board (C.E.G.B.)	United Kingdom
Bureau of Public Roads (B.P.R.)	United States
Centre d'Etudes et de	France
Recherche de L'Industrie des	France
Liants Hydrauliques (C.E.R.I.L.H.)	

These will be referred to in following text by the abbreviations in parenthesis.

The work will be discussed under the following headings:-

2.5.2 Pozzolanic action

2.5.3 Strength

2.5.4 Workability

2.5.5 Durability

2.5.6 Shrinkage

2.5.7 Heat of hydration

2.5.8 Economics of using p.f.a. in concrete

2.5.9 Physical and chemical properties of p.f.a. relating to performance in concrete

2.6.0 Benefication of p.f.a.

2.7.0 Summary of findings.

2.5.2 Pozzolanic action

2.5.2.1 Definitions

Pozzolanic action of p.f.a. is the property in which the engineer is frequently interested as this relates to the progressive gain in strength and hence long term durability of a p.f.a. concrete.

At this stage it would be useful to define a pozzolana (or pozzolan). Three definitions taken from different sources are given as follows:-

i) A pozzolan is a siliceous or siliceous aluminous material which in itself possesses little or no cementitious value but will, in finely divided form and in the presence of moisture chemically react with calcium hydroxide at ordinary temperatures to form

compounds possessing cementitious properties.
(A.S.T.M. 'Definition of terms as applied to Hydraulic cements'(C 219 - 55) 1955 Part 3 p. 201)

ii) Pozzolanas are usually defined as materials which, though not cementitious in themselves contain constituents which combine with lime at ordinary temperatures in the presence of water to form stable insoluble compounds possessing cementing properties. (The Chemistry of Cement and Concrete, F.M. Lea, Chapter 14 p. 414)

iii) Pozzolana is a volcanic ash found near Pozzuoli much used for hydraulic cement. (The Concise Oxford Dictionary 5th Edition)

The author does not wish to propose a synthesis of these definitions but suffice it to say that the material (p.f.a.) being dealt with in this thesis might be described by i) and ii) but certainly not by iii) which alludes to the origin of the name rather than to a description of physical properties. I therefore propose i) and ii) as acceptable definitions.

2.5.2.2 Tests for Pozzolanic activity

Watt and Thorne (8) (B.C.U.C.) 1965 conducted a series of tests on 14 p.f.a.s using several chemical tests, of which the most successful were as follows:-

i) Feret-Florentin method - hydrochloric acid is used to assess the quantity of Silica + Alumina + Ferric oxide in unhydrated and hydrated pozzolana (p.f.a.) - lime mortars.

ii) Lime solution method - similar to i) but the pozzolana (p.f.a.) was allowed to react in a saturated lime solution instead of in a mortar.

The crushing strength of the mortar was then plotted against the acid soluble increment (due to pozzolanic action) for each p.f.a. Results showed a fairly good correlation (positive) between the above properties.

In their final assessment of chemical methods of assessing pozzolanic activity, Watt and Thorne (8) concluded that these methods would be unlikely to be of value for assessing concrete performance in practice.

Lea (9), 1970 states the reasons more clearly with reference to the Fratini-Rio tests and Watt and Thorne's work when he says that although a limited group of pozzolanas may fall approximately in a common curve it is clear that no broad relation exists for other tests on a group of Italian pozzolanas, which did no more than pick out the materials that made the least contribution to strength.

Jones and Gill (10) (C.E.G.B.) 1962 claimed that the chemical method described by Fratini Rio and an accelerated curing method for assessing strength placed 7 p.f.a.s in the same rank order.

2.5.3 Strength

The easiest and most frequently used method of testing for pozzolanic activity is by making a concrete or mortar mix in given proportions often termed the 'control' and replacing part of the cement on a weight or volume basis with a p.f.a. and comparing the strength of the p.f.a. concrete with that of the control at various ages. It has been found through experience that this pozzolanic strength development is usually long term. (4) (11) (18)

Brink and Halstead (11) (B.P.R.) 1956 investigated the behaviour of 34 p.f.a. mortars from 19 different sources in combination with three different cement types varying in alkali and tri-calcium silicate content.

Cement replacements with p.f.a. were made on a solid volume basis using 10, 20, 35 and 50% replacement of cement with p.f.a. All mortars tested were made to a uniform consistency and the ratio of the water required by the p.f.a. to that required by the control, termed 'the water requirement ratio' was determined.

Evidence of pozzolanic activity was indicated by a progressive increase in strength of the p.f.a. mixes compared with the control over a 1 year period.

Pozzolanic Strength Index (P.S.I.)

To determine the relationship between the strength of cement - p.f.a. mortars and the properties of p.f.a. a standard of comparison for strength was selected. This was taken as the average 28 day strength of mortar at 35% cement replacement for the 3 cements used. These P.S.I.s were then plotted against various p.f.a. characteristics such as carbon content, specific surface, grading, % passing No. 325 sieve* average water requirement etc.

The final conclusions were that the tests indicated positive correlations between P.S.I. and % passing No. 325 sieve and negative correlations between P.S.I. and carbon content and finally P.S.I. and water requirement.

Timms and Grieb (12) (B.P.R.), 1956 carried out a series of tests using p.f.a. of widely different fineness but representative of p.f.a.s used in the U.S.A. Air entrainment was included in some mixes and cement replacement was done on a solid volume basis.

Flexural and compressive strength tests were carried out on concrete specimens and revealed 28 day strengths lower than control but 1 year strengths as high or up to 20% higher than control. In general, it was concluded that increasing p.f.a. % led to lower strengths at a given age as did increasing carbon contents.

* 44μm sieve.

Ward (13) (C.E.G.B.), 1954 used a 1:2:4 mix concrete with a water : cement ratio = 0.65 as control. Cement was replaced by p.f.a. by weight at 10, 20, 30 and 40% replacement levels. Effects of the p.f.a./cement ratio, carbon content and fineness upon compressive strength were investigated.

Unexpectedly, no effects of pozzolanic activity were evident at the later ages for any of the replacement levels, in fact the 10 and 20% replacement levels produced slightly higher strengths than the control within the first 28 days. For the 30 and 40% replacement levels 28 day strengths were 85% and 75% of control (0% p.f.a.) respectively with no evidence of pozzolanic activity at greater ages up to 1 year.

For a range of carbon contents (5 - 12%) no appreciable effect upon strength was recorded. With respect to fineness, the coarser p.f.a. showed slightly inferior strengths up to 180 days.

Fulton and Marshall (14) (North Scotland Hydro Electric Board and University of Glasgow), 1956 carried out an investigation connected with the use of p.f.a. in hydraulic structures as a prelude to its use in a large dam being built by the North Scotland Hydro Electric Board. They visited the U.S.A. and reviewed research work from the following institutions:-

University of California

U.S. Bureau of Reclammation

U.S. Corps of Reclammation

U.S. Corps of Engineers

American Portland Cement Association

Ontario Hydro-Electric Commission

University of Glasgow

They concluded that if the concrete is not to withstand its working load until some time after pouring then 20% of cement can be replaced with p.f.a. without impairing its strength. They generally ascertained that a low carbon content was desirable but not essential for adequate strength.

In final conclusion they suggested accelerated testing as a suitable method for comparing the quality of p.f.a. concretes. In this way, p.f.a. from different sources could be quickly assessed without having to wait long periods for test results.

Goodridge and Jackson (15) (C.E.G.B.), 1961 as a sequel to work carried out by J.M. Ward suggested the early loss in strength experienced at high cement replacement levels could be offset by replacement of the fine aggregate fraction in the mix as a means of achieving what they considered to be the optimum p.f.a. : cement ratio, without reducing the cement content of the mix.

They found from work done using different techniques of cement and fine aggregate replacement with p.f.a. that the cement should be replaced on a weight basis and the fine aggregate on a volume basis. Using this method they suggested the most economic mix was obtained using 20% replacement of cement with p.f.a. with a p.f.a.: cement ratio = 0.6. The remainder of p.f.a. was included by replacing fine aggregate (sand) by volume in a basic mix of 1:2:4.

Jones and Gill (10) (C.E.G.B.), 1962 used the formula devised by Goodridge and Jackson to test its validity for early strength concretes using principally p.f.a.s from the North West of England.

Tests were done on the basis of constant workability (VeBe times of 11 - 18 secs) and the control mix was designed to give a strength of 4,000 p.s.i. (28 N/mm^2) at 28 days with a water : cement ratio = 0.62. Water contents were varied to conform within the required workability range. P.f.a./cement ratio was 0.6 and 20% of cement was replaced with p.f.a. according to the Goodridge and Jackson formula.(15)

The summary of findings was as follows:-

i) P.f.a.s from certain power stations were suitable for early strength concretes whilst others were less so.

ii) The percentage passing 300 mesh sieve (53μm) was more important than loss on ignition (often an indication of carbon content). *

* see Halstead (11)

iii) P.f.a. with high carbon contents require more water to give the same workability as control.

iv) Ignition loss correlates negatively with strength.

v) The Goodridge-Jackson formula can form the basis of a rational p.f.a. substitution for cement in concrete.

Bannister (16) (University of Salford), 1962 applied the Goodridge-Jackson formula to mixes with water: cement ratios varying from 0.50 - 0.70 and p.f.a.:cement ratios varying from 0.40 - 0.70 and investigated 7 and 28 day strengths with reference to those obtained from Road Note 4 for ordinary portland cement (O.P.C.). Relationships between accelerated tests (after boiling) and 7 and 28 day strengths were also obtained.

The optimum p.f.a.:cement ratio was found to be 0.40 with those of 0.60 and 0.70 showing lower early values compared with Goodridge and Jackson's formula albeit with p.f.a. from a different source (Agecroft 'C')

A minimum expected strength at 7 days of 80% of boiling strength could cover p.f.a.:cement ratios of 0.40 to 0.60. From this value the 28 day strength could be deduced using curves from Road Note 4.

Jordan (17) (C. & C.A.), 1954 carried out a series of tests on 21 different p.f.a.s involving materials from different power stations in the U.K. operating under different conditions, mixtures of ashes from different sources and in addition he ground some p.f.a.s to achieve a higher specific surface. Control mixes utilised both O.P.C. and Rapid hardening Portland cement with cement: aggregate ratios of 1:5.22 and 1:6.0. Replacement was done on a weight basis at the 25% level. Compressive strengths were obtained up to 1 year. The water:cement + p.f.a. ratio by weight varied between 0.30 and 0.70.

Findings were as follows:-

i) For p.f.a. having ignition loss of less than 10% and similar fineness to Portland cement the compressive strength up to 28 days was = 67% of control. This difference in strength gradually disappeared until at 1 year p.f.a. concretes had similar strengths to the control.

ii) There was a suggestion that p.f.a. samples with high ignition loss and coarse grading yielded lower strengths than typical ashes and that p.f.a.s with unusually high specific surface have higher strengths.

iii) Within the test range, relative strengths seemed to be unaffected by cement type, mix proportions or curing conditions (water and air at ambient and standard conditions).*

* B.S. 1881 Part 3. (46)

Venuat (18) (C.E.R.I.L.H.), 1962. This investigation was designed to find the importance of the physical and chemical characteristics of 2 portland cements and 3 p.f.a.s upon the physical characteristics of cement/p.f.a/sand mortars. Mortars were made up containing up to 70% cement replacement by weight with p.f.a. The proportions of the control were 1:3 by weight* and water:cement + p.f.a. ratios of 0.45, 0.50 and 0.55 were used. Cement (clinker + gypsum) and p.f.a. were ground in the laboratory and subsequently mixed in the required proportions to form 32 cement/p.f.a. mixtures varying from 0 - 70% p.f.a.

Strength results were obtained by using compression and flexural tests on 40 x 40 x 160 mm mortar prisms and were presented in two ways:-

i) Strength versus % p.f.a. for equal ratios of water:cement + p.f.a.

ii) Strength versus % p.f.a. for equal plasticity.

The results showed that for all mixtures the strength of mortar increased with increasing age and decreasing % p.f.a. resulting in a family of curves similar to that shown by Lea. (19)

Strength values for equal plasticity were superior to those for equal water:cement + p.f.a. ratio. This was apparently due to the lower water demand for equal plasticity of the p.f.a. mixtures.

* cement:sand.

2.5.4 Workability

Comparatively little work has been done upon the workability of p.f.a. concretes and most comments therefore tend to be subjective rather than objective evaluations of workability performance.

The results of the more important investigations are summarised below.

Venuat (18) (C.E.R.I.L.H.), 1962 in conjunction with the work just described in sub-section 2.5.3, used a flow table (table à secousse) to assess the plasticity of his p.f.a. mortars. The plasticity was assessed by measuring the diameters of a cone of concrete before and after vibration on a 'table à secousse' (a sort of horizontal dynamic slump test).

Using water:cement + p.f.a. ratios of 0.45, 0.50 and 0.55 he found that between 0 and 40% cement replacement the plasticity significantly decreased (increased workability). Between 40 - 70% cement replacement plasticity was roughly constant and above 70% there was a slight increase in plasticity (decreased workability).

Tran-Thanh-Phat (20) (C.E.R.I.L.H.), using a similar form of test, found in concurrence with Venuat that for equal plasticity the water:cement + p.f.a. ratio decreased from 0.52 to 0.45 for between 0 and 40% cement replacement with p.f.a. These tests were also carried out on a 1:3 cement + p.f.a.:sand mortar mix.

Jolly (21) (Salford University), 1965 using the compacting factor test showed on the other hand that mixes with low water:cement ratio and high cement content resulted in reduced workability with increasing p.f.a. However, cement and fine aggregate replacement were used here and hence the increased water demand of the finer material (p.f.a.) would have cancelled out the lubricating effect of the p.f.a. cenospheres. (6)

Jordan (17) (C. & C.A.), 1954 using Slump and Compacting Factor tests suggested that samples having an unusually high ignition loss (20 - 40%) accompanied by coarse grading have lower workability. (26)

Timms and Grieb (12) (B.P.R.), 1956 used the slump test to ensure constant workability for all their mixes. Actual values varied between (60 - 100 mm) 2.5 - 4 ins. for air entrained and non-air entrained p.f.a. concretes.

Brink and Halstead (11) (B.P.R.), 1956 did not use standard concrete workability tests as their tests were conducted using 2 in (50mm) cubes made from a 1:2.75 cement:sand mortar. All mortars were made to a uniform consistency using A.S.T.M. (C 109 - 49)'Method of test for Compressive Strength of Hydraulic Cement Mortars'.

Cannon (22) (Tennessee Valley Authority), 1968 in his work on proportioning p.f.a. mixes for strength and economy refers to the water requirement of p.f.a. mixes in relation to a control but omits reference to values of workability. His mix design method assumes that the water:cement ratio of the desired control mix will give the required slump.

Jones and Gill (10) (C.E.G.B.), 1962 reference has already been made to their use of the VeBe test for ensuring standard consistencies of p.f.a. concretes.

2.5.5. Durability

Durability (defined in the Oxford Dictionary as 'lasting, not transitory resisting wear and decay') like workability means different things to different people and is equally difficult to quantify.

Engineers may measure durability in two ways i.e.:- i) directly as in the measurement of physical properties after the concrete has been exposed to aggressive conditions e.g. freeze/thaw, sulphates etc., or ii) indirectly (i.e. by inference) by measuring some physical property which from past experience or logical deduction is likely to affect its resistance to attack by aggressive elements e.g. porosity/permeability, strength etc.

The review of durability work which follows refers essentially to the direct type of test.

2.5.5.1 Immersion in aggressive solutions

Miles (23) (C.E.G.B.), 1968 studied the effect of five aggressive solutions (including various concentrations of magnesium and sodium sulphate together with one solution consisting of a mixture of magnesium, sodium and calcium sulphate) upon medium (30 N/mm^2) and low (14 N/mm^2) strength p.f.a./O.P.C. and p.f.a./S.R.C.* concretes. The controls were designed in accordance with Road Note 4 with suitable modifications to allow for the characteristics of available materials. The proportions of p.f.a. included in the control for equivalent strength were obtained using a method proposed by Smith (57). The medium and low strength concretes allowed cement reductions of 5% and 16% respectively.

A statistical analysis upon the results revealed the following:-

i) The type of solution in which the concrete was immersed had a significant effect upon compressive strength of test cubes but this was less marked than the effects of age, mix type, and p.f.a. source.

ii) For the same exposure O.P.C.-based p.f.a. concretes of 'low' strength tended to show a greater rate of strength development with age than non p.f.a. mixes. However, this effect was reversed for 'medium' strength p.f.a. concretes.

iii) In S.R.C.* concretes p.f.a. mixes were significantly stronger than control.

* Sulphate Resisting Cement.

Miles concluded that there was a need for exposure tests of longer duration than 12 months which was the period of this investigation.

Venuat (18) (C.E.R.I.L.H.), 1962 immersed 40 x 40 x 160 mm mortar specimens with a cement:aggregate ratio of 1:3 and water:cement ratio = 0.50, in a 5% magnesium sulphate solution. Initially specimens were stored for 28 days and 90 days in a neutral solution (tap water). The period of conservation in the sulphate solution was 270 days. All specimens were manufactured using 2 cements, Clinker I (low C_3A) and Clinker II (high C_3A) and one p.f.a. at 0, 20, 30, 40, 70 and 90% replacement levels. Sulphate resistance was determined by noting the relative expansion of the specimens stored in neutral (tap water) and sulphate solutions.

Findings were as follows:-

i) Between 0 and 40% p.f.a., Clinker I mortar revealed little change. Above this level large relative expansions occurred and specimens started to disintegrate.

ii) Between 0 and 40% p.f.a., Clinker II mortars improved their resistance against sulphate attack. This improvement was maintained up to a 70% p.f.a. level and resistance deteriorated with further increase in % p.f.a.

Venuat concluded that there were three factors mutually at work namely:-

(a) % of C_3A in clinker :- large % of C_3A makes concrete more vulnerable therefore a large % of cement replacement can be affected consequently improving its resistance to attack up to a certain replacement level.

(b) Strength of mortar :- as % p.f.a. increases mortar strength weakens (for a given age) until it is unable to resist expansive forces (however small) within it.

(c) Porosity of mortar :- influences the ease with which aggressive solutions can penetrate specimens and thus combine with the C_3A.

2.5.5.2 Freeze/Thaw exposure

Timms and Grieb (12) (B.P.R.), 1956 found that for non-air entrained concretes the inclusion of p.f.a. did not enhance the resistance to freeze/thaw exposure. Assessment was made by determining the relative decrease in elastic modulus of prismatic concrete specimens for a pre-determined number of cycles ; 1 cycle lasting for 24 hours with temperatures ranging from $10^{\circ}F$

to 70°F (-12° to 21°C).

Venuat (18)(C.E.R.I.L.H.), 1962, found that specimens containing 70% cement replacement with p.f.a. disintegrated after 150 freeze/thaw cycles each cycle consisting of air exposure at -20°C for 16 hours and 8 hours in water at +20°C. Specimens containing 30% cement replacement were a little less resistant than the control specimens. All specimens were initially stored in water at +20°C up until 28 days when they were transferred to the conditions outlined above. All tests were carried out using a constant water:cement ratio and were subjected to a maximum of 200 cycles.

Venuat concluded that the lower resistance of the specimens with a high % of p.f.a. was due to the interaction of two factors:-

i) Lower tensile strength.

ii) Higher porosity.

2.5.5.3 Alkali-aggregate reaction

Brink and Halstead (11) (B.P.R.), 1956, found that inclusion of p.f.a. in a mix reduced the alkali-aggregate reaction between cement and reactive opal to a negligible amount at 30% cement replacement by volume. Assessment was made by measuring relative change in length of prismatic specimens containing cement, fly ash (p.f.a.) and opal.

2.5.5.4 Influence of porosity

Venuat (18) (C.E.R.I.L.H.), 1962, concluded that the resistance of mortar specimens to freeze/thaw conditions or sulphate attack was largely a function of the porosity and found further that the porosity of mortar, as measured by capillary absorption, increased with increasing % replacement of cement with p.f.a. at the same water:cement ratio. In practice, for the same plasticity (workability) the water:cement ratio could be reduced and thus offset the increasing % of p.f.a.

2.5.6 Shrinkage

Timms and Grieb (12) (B.P.R.), 1956, found that p.f.a. concretes showed less shrinkage upon drying than concrete without p.f.a. Cement replacement levels were $= 16^2/_3$ % and $33^1/_3$ %.

Venuat (18) (C.E.R.I.L.H.), 1962, established that the relative shrinkage after 90 days exposure in air showed little variation for increasing % p.f.a. except for the high alkali cement where a slight reduction was observed with increasing % p.f.a.

2.5.7 Heat of hydration

Terrier and Moreau (24) (C.E.R.I.L.H.), 1966 in their research into the mechanism of pozzolanic activity found that the heat of hydration was reduced by up to 50% at 7 days for 30% p.f.a. mortar.

Venuat (18), 1962, found that the heat of hydration decreased (determined at 12 hours, 3 days and 7 days) as the % of p.f.a. was increased and further that there was a strong correlation between the heat of hydration at 12 hours, 3 days and 7 days and the 7 day, 28 day and 90 day strengths respectively.

Both of the above used calorimetry methods and mortar specimens.

2.5.8 Economics of using p.f.a. in Concretes

This field is probably the least explored in research terms probably because prevailing economic conditions are a capricious function of time and as a result relative costs of materials are always changing.

Goodridge and Jackson (15) (C.E.G.B.), 1961, suggested that to obtain best early strength results fine aggregate replacement in addition to cement replacement was preferred.

In the context of 1973 relative prices of materials at the 10% cement replacement level using the example submitted in their paper the cost advantage of p.f.a. concrete was 2.5%.

As the ratio of fine aggregate cost to p.f.a. cost is currently declining, the cost advantage of cement and fine aggregate replacement is rapidly being eroded.

Cannon (22) (T.V.A.), 1968, said that the economy of using p.f.a. depends entirely on the relative cost of p.f.a. and cement and the strength requirements of the concrete. His mix design methods included an allowance for the p.f.a.:cement cost ratio in terms of the required 28 day and 90 day strengths.

2.5.9 Physical and chemical properties of p.f.a. relating to performance

The water requirement of p.f.a. is extremely important because this ultimately affects the amount of water available for hydration and lubrication which in turn affects the workability, strength and durability of the concrete.

Minnick, Webster and Purdy (25, 26) 1971, using published data over a 35 year period from widely divergent sources found that the % retained (or passing) the No. 325 sieve (45 μm) and the % loss on ignition (unburnt fuel) both correlated individually and as a product extremely well with the relative water requirements of p.f.a. concretes.

In addition, they found a high correlation between specific gravity and ferric oxide content of p.f.a. Specific gravity was also affected to a lesser extent by ignition loss.

2.6.0 Benefication of p.f.a.

Reference has previously been made to the problems of high ignition loss and coarse grading of p.f.a. To offset these problems some companies e.g. Southern Fly

Ash (U.S.A.) (27) and Pozzolanic Pty Ltd (England) have installed equipment (usually rotary air separators) to remove the deleterious material. The separation criterion usually ensures that at least 95% of the derived product passes a No. 325 sieve (44μm). This has the twofold effect of increasing the fineness of material and reducing the ignition loss (since a high proportion of the coarser particles is unburnt fuel) thus ensuring that material consistently conforms to the desired specification.

Stirling (28) (Stirling Sintering Co., Pittsburgh, U.S.A.), 1965, has suggested that the concept of total utilisation should be looked at more closely. By the installation of a sophisticated separation system involving cyclone, magnetic separation combined with pelletisers and sintering grates a plant can produce simultaneously the following products:-

i)	carbon	-	for the removal of flue gases or recycled as fuel.
ii)	pozzolan	-	as cement replacement in concrete.
iii)	lightweight aggregate	-	for concrete.
iv)	iron	-	for use in steel plants.

The total utilisation of p.f.a. could have a large effect upon the economics of p.f.a. utilisation, for example, companies which presently select for one of the above could substantially increase their profitability by the total utilisation concept.

2.7.0 Summary of findings

From the foregoing, there appears to be broad agreement that the inclusion of p.f.a. in concrete, principally as a cement replacement material, affects the concrete as follows:-

i) Increases the strength at later ages (usually after 28 days).

ii) Reduces the early gain in strength.

iii) Improves workability.

iv) Reduces the heat of hydration.

v) Increases the resistance to chemical especially sulphate attack up to a certain level of replacement.

vi) Reduces the cost of concrete by reducing the quantity of cement and avoiding heat of hydration problems.

Further, regarding the quality of p.f.a. it has been suggested that a high ignition loss and increasing coarseness is detrimental to concrete quality.

It also appears that there are areas about which there is still some contention, and these are listed as follows:-

i) The optimum cement (or fine aggregate) replacement level.

ii) The best method of including p.f.a. in concrete whether by volume or weight replacement or further by cement or fine aggregate replacement.

iii) Whether the benefication of p.f.a. is either beneficial for the concrete or economic for the producer.

iv) The benefits of p.f.a. in reducing shrinkage and increasing resistance to freeze/thaw conditions.

3.0 Research Objectives

3.1 Introduction

The preceding chapter reviewed previous research work. This chapter outlines and discusses the cost and performance criteria used to promote the use of p.f.a. in concrete in the light of some of this previous research and further considers the implications of CP 110 'The Structural Use of Concrete' (29) in this context. The chapter concludes with a discussion and summary of the principal aims and objectives of this investigation.

3.2 Cost and Performance

In choosing structural materials the engineer must consider two important aspects namely their cost and performance.

The three principal constituents of concrete are listed as follows, in order of their cost related to that of cement:-

Constituent	Cost ratio (1973 prices)
Cement	1.0
Aggregate	0.16
Water	≈0 (but rising)

If a fourth constituent e.g. p.f.a. is included the order is as follows:-

Constituent	Cost ratio (1973 prices)
Cement	1.0
P.f.a.	0.32
Aggregate	0.16
Water	≈0 (but rising)

It is apparent that inclusion of p.f.a. as a cement replacement tends to reduce the concrete cost whilst its inclusion as an aggregate replacement tends to increase the cost.

The decision whether or not to include p.f.a. and if so, at what level it should replace the other constituents must therefore depend upon the following:-

i) The relative cost of a p.f.a. and non p.f.a. concrete.

ii) Conformity of either concrete to the required performance specification.

The first aspect, relating to the economic level of replacement cannot be established until the second i.e. performance in terms of the specification has been ascertained. Therefore further discussion of the former will be left until the chapter on mix design (Chapter 5) and this chapter and the subsequent one (Chapter 4) will concentrate upon the performance/specification aspects.

3.3 Concrete properties

Before proceeding further, the author feels that a summary of the alleged benefits of including p.f.a. in concrete would be useful. These are as follows:-

i) Increased workability.

ii) Increased strength at later ages.

iii) Lower heat of hydration.

iv) Increased resistance to chemical attack.

v) Increased resistance to freeze/thaw action.

vi) Reduced shrinkage.

Unfortunately, both time and resources precluded the author from considering the verification of all of these but it was felt that in the large majority of cases the overriding considerations of most engineering specifications are as follows:-

i) Workability.

ii) Strength.

iii) Durability.

It is to be conceded that heat of hydration is an important factor determining the use of p.f.a. in large mass concrete structures but previous experience and research has been almost unanimous in its agreement about this particular benefit. (4) (18) (20)

Evidence regarding p.f.a.'s influence on the freeze/thaw and shrinkage characteristics of concrete is less conclusive. However, in the former case it appears to be detrimental only at large (> 40%) cement replacement levels and in the latter case to be at best beneficial and at worst ineffective. (12) (18)

3.4 Specification, Compliance and CP 110 (29)

In 1972 the British Standards Institution produced CP 110 'The Structural Use of Concrete', a code of practice containing recommendations for the design and construction of concrete structures. Of particular interest to the author is section 6.0 'Specification and Workmanship'. This contains references and recommendations regarding permissible types and quantities of materials to be used in concrete together with a brief outline of the appropriate tests to be employed to establish certain concrete and constituent properties.

The author will now briefly discuss the use of p.f.a. in concrete in the context of CP 110 with particular reference to constituent materials, workability, strength and durability.

To begin with, a brief outline in paraphrase of the relevant clauses will be given. From this will be extracted the details which the author feels are most pertinent to this project. Appropriate clause numbers are included in parenthesis and quoted extracts are in inverted commas.

3.4.1 Constituent materials of concrete (6.2)

Cement (6.2.1)

"The cements used should comply with the following British Standards:

B.S. 12, 146, 1370, 4027, 4246, 915, 4248.

Where cements other than those complying with the requirements of B.S. 12 or B.S. 146

are used, account should be taken of their properties and any particular conditions of use."

Aggregates (6.2.2)

"In general, aggregates should comply with the requirements of the following British Standards:

B.S. 882, 1201, 877, 1047, 3797, 4619.

The engineer may specify or approve on request the use of aggregates including types and gradings not included in British Standards provided there are satisfactory data on the properties of concrete made with them."

Admixtures (6.2.4)

"Pulverised-fuel ash (6.2.4.3). The fineness zone and the maximum sulphate content of p.f.a. in accordance with B.S. 3892 should be specified.

Pulverised fuel ash should not be used in conjunction with a cement complying with the requirements of B.S. 4027 in concrete required to be resistant to sulphates."

3.4.2 Workability (6.4.2 and 6.8.4)

C.P. 110 states that the workability of fresh concrete should be such that the concrete is suitable for the conditions of handling and placing so that after compaction it surrounds all reinforcement tendons and ducts and completely fills the formwork.

Workability should be assessed by means of the following tests:-

Test	Limits
Slump	± 25 mm or ± $\frac{1}{3}$ of the required value, whichever is the greater.
Compacting Factor	± 0.03 where the required value ≥ 0.90.
	± 0.04 where the required value > 0.80 < 0.90
	± 0.05 where the required value < 0.80.
VeBe	± 3 secs. or $\frac{1}{5}$ of the required value whichever is the greater.

3.4.3 Strength and Durability

Grade designation (6.3.2 - see also 6.8.2 and Table 47)

"The grade of concrete* required will depend

* numerically equivalent to the characteristic strength; that strength below which not more than 5% of test results shall fall (6.8.2.1)

partly on the particular use and the characteristic strength needed to provide the structure with adequate ultimate strength (see Table 47 C.P. 110) and partly on the exposure conditions and the cover provided to any reinforcement or tendons.
The characteristic strength is that determined from test cubes at 28 days for concrete with any type of cement excluding high alumina cement concrete."

<u>Minimum cement content</u> (6.3.3 - see also Tables 48 and 49)

"One of the main characteristics influencing durability of any concrete is its permeability.
With strong dense aggregates a suitably low permeability is achieved by having a sufficiently low water/cement ratio by ensuring complete compaction of the concrete and by ensuring sufficient hydration of the cement through proper curing methods."

To satisfy the above, Table 48 gives details of the "minimum cement content required when using a particular size of aggregate in a Portland cement concrete to provide acceptable durability under appropriate conditions of exposure" and Table 49 similarly gives the "minimum cement content required for a particular type of cement to provide acceptable durability under a particular degree of sulphate attack." In the latter case, particular stipulations are laid down regarding the appropriate maximum free water/cement ratio to be used for each condition.

The author wishes to make the following observations regarding the above paraphrased extracts from C.P. 110.

i) Pulverised fuel ash is classified specifically as an admixture but apparently the designer is not precluded from constituting a 'cement' by mixing or intergrinding O.P.C. with P.F.A. or even Blastfurnace slag as is done in France. (4)

ii) There is particular reference to the fineness and sulphate content of p.f.a. but none to ignition loss; a factor thought to have a large influence upon performance both with respect to average quality and variability. (25) (26) (30)

iii) Workability is recommended to be measured by using the three standard (31) workability tests e.g. Slump, Compacting Factor and VeBe.

iv) Characteristic strength is determined from test cubes at 28 days. (32)

v) There is no clear definition of what is meant by 'minimum cement content'. For example could 'minimum cement content' ≡ minimum p.f.a. + O.P.C. content?

vi) By specifically referring to particular types of cement and aggregate in Table 49, use of p.f.a. in concretes exposed to sulphate attack is precluded.

vii) There is no recommended test for durability although reference is made to the importance of permeability in this respect and certain recommendations regarding minimum water/cement ratios and cement contents are stated.

3.4.4 <u>Discussion of Objectives</u>

The author feels that although the role of p.f.a. as an admixture should be maintained its role as an additive in blended cements might warrant further consideration especially with a view to its inclusion in Table 49 of

C.P. 110. In this context the 'minimum cement content' would of necessity be interpreted as minimum O.P.C. + p.f.a. in addition to any other ingredient included in such a proprietary cement.

Its inclusion in Table 49 as an admixture is more difficult since this would necessitate stating both the quantity of O.P.C. and p.f.a. to be included separately and unless the consistency of the latter can be improved, the optimum quantity of p.f.a. to be included would vary considerably according to the source of material.

The author therefore considered that the primary purpose of this project was firstly to establish the principal differences between treated (P 1) and untreated (P 2) p.f.a. and secondly to establish to what degree these differences, if any, would be reflected in the behaviour of fresh and hardened concrete incorporating each material. These results could then be viewed with respect to both performance; by comparing the results with an O.P.C. control mix and economics; by balancing cost against performance. The ways in which performance was assessed and the techniques of incorporating the p.f.a. in concrete are discussed in subsequent chapters. (Chapter 4 and Chapter 5 respectively)

The author also felt that although some methods of measuring concrete performance have been long established (e.g. Slump and compressive cube strength) it would be appropriate to take the opportunity of comparing these tests with those more recently developed such as

Compacting Factor and VeBe for workability and cylinder splitting (indirect tensile) and ultra-sonic pulse velocity for strength. All of the above are now recognised British Standard tests (33) but there is comparatively little correlative data for p.f.a. concretes using these tests.

In addition, the author considered that although the standard workability tests are widely used, he would take the opportunity of comparing the British Standard tests with a more fundamentally based 2 point test developed by G.H. Tattersall of Sheffield University. (34)

3.4.5 Summary of principal aims and objectives

i) The comparison of the properties of treated (P 1) and untreated (P 2) p.f.a. material collected from a single source (Fiddlers' Ferry 'B' Power Station via Pozzolanic Pty Ltd).

ii) The comparison of the performance of fresh and hardened concretes incorporating P 1 and P 2 with those of an O.P.C. control in terms of workability, strength and durability.

iii) From the results of i) and ii) the establishment of a basis for incorporating p.f.a. in concretes designed to resist sulphate attack as outlined in Table 49 CP 110.

iv) The determination of the most economic mix or range of concrete mixes incorporating each type of p.f.a. material which compare most favourably, in terms of workability, strength and durability, with those of a chosen O.P.C. control (containing no p.f.a.).

v) The correlative comparison of the workability and strength tests applied to the whole range of concrete mixes.

CHAPTER 4

TESTING METHODS AND MATERIALS

4.0 Testing Methods and Materials

4.1 Introduction

In this chapter attention will be paid to the definition, context and assessment of the workability, strength and durability of concrete in terms of previous work and available tests. This will be followed by a brief description of constituent tests together with details of the particular constituents used in this investigation.

4.2 A review of the Testing of Concrete properties

4.2.1.0 Workability

Comprehensive definitions of workability are difficult to find but a few attempts on near definitions will be referred to as follows:-

Neville (35) does not define workability but says 'The strength of concrete of given mix proportions is very seriously affected by the degree of compaction; it is vital therefore, that the consistence of a mix is such that the concrete can be transported, placed and finished sufficiently easily without segregation'.

Ritchie (36) divided rheology (or workability) into three main areas namely:-

i) Stability - bleeding and segregation.

ii) Compactability - relative density.

iii) Mobility - viscosity, cohesion and angle of internal resistance.

Tattersall (37) suggests that there is not yet any satisfactory definition of workability and none is likely to emerge in the near future. However, he describes the term as meaningful in a relative sense and suggests three groups of terms to describe the behaviour of fresh concrete:-

i) Qualitative

including - Workability (a general term)
Flowability
Compactability
Stability
Finishability
Pumpability
Extrudability

ii) Quantitative

including - Slump
Compacting Factor
V B time

iii) Quantitative Fundamental

including - Viscosity
Yield value
Mobility.

It is apparent from this classification that terms in different classes are interrelated e.g. the pumpability of concrete will largely be a function of its viscosity, yield value etc. and 'compacting factor' a measure of a concrete's 'compactability' etc.

Ritchie (36) alleged that the term workability has been greatly misused; many of the workability tests being purely relative and there being no correlation between the type of test and the application of its findings.

Tattersall (37) suggests the major criticism of existing workability tests is that they are single point tests i.e. that one measurement is made at a particular rate of shear. For example two different concretes A and B may have the same compacting factor but A will pump and B will not indicating that the only workability characteristic that they probably have in common is their compacting factors which is a test at one particular rate of shear.

4.2.1.1 The 2 Point Test (34) (38)

Tattersall (37) suggests that there is strong evidence that in practice concrete conforms to the Bingham (rather than the Newtonian) model whose flow properties are defined by the constant ratio of stress to shear rate.

He further suggests that the application of different rates of shear to a concrete and determination of the corresponding shear stresses would provide a much more comprehensive and a unique description of concrete behaviour.

If shear rate is plotted against shear stress an indication of the dynamic resistance - or plastic viscosity - of concrete can be obtained (from the slope). Extrapolation of the line to the abscissa (zero shear rate) gives an indication of its static resistance (yield).

The problems associated with such a test are as follows:-

i) choosing a suitably robust and sensitive apparatus,

ii) measurement of shear rate and shear stress,

iii) segregation of concrete during test,

iv) correlating test data with that from existing workability tests,

v) repeatability of test,

vi) calibration,

vii) cost of apparatus and availability.

Preliminary trials with a Hobart Food Mixer model AE 200 had been carried out at Sheffield University with a view to its application for the above purpose. A tachometer was used to determine the rotational speeds of the epicyclic mixer blades and the torque (≡ shear stress) was measured using a wattmeter.

Calibration of the mixer to monitor performance consistency was to be determined using a high viscosity Newtonian fluid (of known viscosity). Tate and Lyles Golden Syrup appeared to be suitable but as the result of further investigation carried out by the author, its viscosity was found to be highly temperature sensitive within the normal working range (15 - 25^{o}C)

The author, however, felt that inclusion of this test in the program might provide useful information regarding the more fundamental behaviour of concrete and it was included finally in the program.

4.2.1.2 <u>Selection of workability tests to be used in the investigation</u>.

As the result of investigation into previous work the author felt that the tests listed below should be included in the investigation.

i) Slump

ii) Compacting Factor

iii) VeBe

iv) 2 Point Test.

<u>Slump/Compacting Factor/VeBe</u>

The limitations of the above tests have been described in detail by many people but for the following reasons the above tests were considered for use in the experimental work undertaken in this thesis:-

i) They are representative of current site and laboratory tests throughout the western world. (39)

ii) They are British Standard tests.

iii) They are all relatively simple to perform.

iv) They have all been used in the assessment of p.f.a. concretes.

In addition the flow table test was considered but as it had been only occasionally used and then mostly with mortars (18) (24) it was not carried further.

The 2 point test (34) (38)

This test was included for the following reasons:-

i) It has a more fundamental emphasis than existing tests.

ii) It is a more discriminating test than the single point tests (e.g. Slump, C.F., VeBe).

iii) Its sensitivity range was likely to be better than existing tests i.e. at high and low w/c ratios (40)

iv) A correlation between it and single point tests might be useful for its further application.

In the event owing to delivery problems of the AE 200 it was not possible to carry out all of the 2 point tests contemporarily with the other workability tests. In addition, tests were carried out using two different hooks (nominally of the same type). Their geometrical similarity enabled results from the two hooks to be combined using graphical methods.

4.2.2.0 Strength

Strength tests can be divided into two main categories, destructive and non-destructive. The former measure the strength directly by the destruction of specimens in compression or tension whereas the latter by measuring properties such as the elastic modulus or the pulse velocity give an indirect indication of strength using appropriate calibration charts.

4.2.2.1 Destructive Tests

In the U.K. and in most other countries the compressive strength test is the most widely used method of determining concrete strength. The usual age of test is 28 days (for ordinary Portland cement concrete) for quality control purposes but the 7 day strengths and accelerated tests using high temperature curing can be used to assess concrete strength. Most compressive strength tests utilise concrete cubes or cylinders.

In recent years the Indirect Tensile strength (Brazilian) test has gained favour over the cube test where the tensile property of concrete is important e.g. road pavements.

Flexural strength tests on concrete prisms have the advantage of combining two tests in one specimen, as the broken halves from the Flexural strength test can be tested in compression. This latter is known as the 'equivalent cube' method. (32)

Relationships between the above tests have been studied by many researchers and these will be referred to later in the text.

4.2.2.2 Non-destructive tests (N.D.T.)

Non-destructive testing of concrete has until recently not been extensively used in assessing concrete strength. Its use hitherto was restricted to the laboratory and isolated instances of suspected poor workmanship i.e. detection of honeycombing and cracks etc.

The failure of High Alumina Cement concrete beams at the Sir John Cass School, Stepney (41) has, however, resulted in a wider realisation of N.D.T. potential for the indirect assessment of concrete strength especially Ultra-sonic pulse velocity and Rebound hammer tests. (33) (42)

Both of the above tests were considered as candidates for inclusion in the testing programme at an early stage but it was decided that the Rebound hammer technique in the form of the Schmidt Hammer was not suitable for testing very young concretes, before destructive testing, owing to minor damage caused by the impact of the spring loaded mass. The Ultra-sonic pulse velocity method was included as the specimens used for the Flexural strength testing could be monitored up to the testing date. Two further advantages of the U.S.P.V. technique over the Rebound hammer method were firstly the latter's surface sensitivity compared with the former; giving possibly an incorrect assessment of the internal characteristics of the specimen and secondly the greater versatility of the U.S.P.V. technique (i.e. for crack detection as well as strength assessment) meant that it was likely to be more widely adopted than the Rebound hammer methods.

4.2.2.3 Relationship between pulse velocity and strength

The pulse velocity (V) of an ultra-sonic pulse through concrete is related to the dynamic modulus (E) Poissons ratio (ν) and density (ρ) of the concrete by the expression (33)

$$V = \sqrt{\frac{E\,(1 - \nu)}{\rho\,(1 + \nu)\,(1 - 2\nu)}}$$

It has been found further that if

σ_c = compressive strength of concrete

V = pulse velocity

A and B are constants

the compressive strength of concrete is related to the pulse velocity by the expression

$$\sigma_c = Ae^{BV} \qquad \text{(for a particular concrete mix)}$$

Taking logs gives

$$\ln \sigma_c = \ln A \div B\,V$$

giving an equation of the form

$$y = mx + c \qquad (43)$$

It has been subsequently found by the author that a similar relationship appears to hold between indirect tensile strength and pulse velocity (see sub-section 9.3.8)

4.2.2.4 Selection of strength tests to be used in the investigation

The initial selection of tests to be used reflected a desire to represent current testing practice in the U.K. and abroad combined with a regard of likely developments in future testing practice. The selected tests are listed as follows:-

	Test	B.S. No.
i)	Compressive Strength	B.S. 1881 Part 4
ii)	Indirect Tensile Strength	B.S. 1881 Part 4
iii)	Flexural Strength and Equivalent Cube	B.S. 1881 Part 4
iv)	Ultra-sonic Pulse Velocity	B.S. 4408 Part 5

The Flexural Strength (Modulus of Rupture) test was subsequently deleted from the testing program after mix No. 68 as by this time it was felt that sufficient data had been obtained to draw a meaningful comparison with the Indirect Tensile test. Hence previous work done on p.f.a. concretes which used the Flexural test could now be compared with the test results of this project. Furthermore, the flexural test is relatively extravagant in its use of materials, time and storage space and its subsequent omission allowed an acceleration of the mix program.

4.2.3.0 Durability

In deciding upon tests for durability the author had to consider four major factors:-

i) Previous work on testing p.f.a. and other concretes for durability.

ii) Codes of practice relevant to the above (C.P. 110 Tables 48 and 49).

iii) Type of specimens to be tested.

iv) Resources available for testing.

Considering i) and ii) two testing methods immediately presented themselves namely:-

a) Freeze/thaw exposure and

b) Immersion in aggressive solutions.

a) was immediately discounted as facilities were inadequate to undertake a large investigation of this nature. The author therefore chose b).

4.2.3.1 Immersion in aggressive solutions

The next choice to be made was the solution (or solutions) in which to immerse specimens and the level of concentration; bearing in mind i) the short duration of the research period and ii) previous work done in the field. (8) (23)

The principal chemicals used in previous assessments of resistance of p.f.a. concretes to chemical attack are as follows:-

i)	Calcium Sulphate	-	$Ca\ So_4$
ii)	Sodium Sulphate	-	$Na\ So_4$
iii)	Magnesium Sulphate	-	$Mg\ So_4$

A combination of these was also tried. (23)

Previous experience has shown that $Mg\ So_4$ has generally the most destructive effect upon concrete owing principally to two factors:-

i) Combination of C_3A (tri-calcium aluminate) with sulphate in $Mg\ So_4$ to form calcium sulpho aluminate, and

ii) The formation of $Mg\ (OH)_2$ (magnesium hydroxide) which upsets the equilibrium of the calcium silicate hydrates (especially C_3S hydrate) causing a second destructive action. (76)

In view of the compound action of magnesium sulphate and the short duration of the intended exposure, a 3.5% (anhydrous) solution of magnesium sulphate was chosen as the aggressive solution; a similar concentration to that used by Miles. (23)

4.2.3.2 Testing methods for detecting attack by sulphates

There has been much controversy and discussion regarding the testing of concrete specimens subjected to sulphate attack.

A summary of methods considered by the author is as follows:-

i) Strength tests.

ii) % weight loss.

iii) Ultra-sonic Pulse velocity/Electrodynamic.

iv) Surface area depletion.

v) Volume change - length change.

All of the above are quantitative tests with the exception of iv) which although usually a qualitative test has been developed into a quantitative type by measuring corner depletion. (44)

Strength tests were considered unsuitable by the author because of the large number of specimens necessary to carry out what was a subsidiary part of the project.

% weight loss was considered a simple and quick method of determining extent of deterioration and proved to be effective. (45)

Ultra-sonic pulse velocity was a previously untried method probably because of the surface nature of sulphate attack but the author considered that if the ends were suitably protected with grease the coupling of transducers would present no problem and further that for particularly susceptible concretes a dramatic change in ultra-sonic pulse velocity might be apparent. In addition, the U.S.P.V. test can be carried out with specimens continually immersed in water (using suitable transducers) and this would facilitate monitoring. The electrodynamic method was considered suitable but lack of time in the program precluded its use.

Surface area depletion as used by B.R.E. was considered too tedious and the author decided that the initial period of immersion was too short for effective assessment to be made.

Volume change as determined by % change in length has been used extensively (18) (45) but this method is usually carried out on mortar specimens. For reasons of time and convenience however it was felt that this property might well be determined at a later stage, should the period of immersion be prolonged, by comparison with control specimens.

It was finally decided to monitor resistance to sulphate attack by the following:-

i) Determination of % weight loss of 100mm cubes.

ii) Determination of % change in U.S.P.V. of 100 x 100 x 500mm prisms.

The principal reasons for choosing these methods were that they were easy to execute and allowed continuous monitoring of specimens; for an extended period if necessary. Subsequently, only % weight loss has shown any significant change and U.S.P.V. measurements although recorded have been omitted from the text. Monitoring of specimens is still in progress.

It was decided that all specimens should be cured in standard (46) conditions for the first 28 days and then be placed in 3.5% (anhydrous) magnesium sulphate solution.

4.3 The testing of constituent materials.

4.3.1 Influential factors

Reference has been made to the importance of ensuring that the variability of materials is kept to a minimum. However, applying large numbers of exhaustive tests to materials can be both time consuming and counter productive in the long run by providing too much information from which to draw any conclusion.

For this reason, it was decided to restrict these tests to the minimum necessary to comply with two major requirements namely:-

a) to ensure good quality control

and

b) to highlight any differences between physical characteristics of constituents which might be related to their behaviour in concrete.

With reference to b) previous tests have shown that suitability of p.f.a. for use in concrete is unlikely to be indicated by a single test but the measurement of certain properties such as % passing No. 325 (44μm) sieve and % ignition loss have been shown to correlate well with the water demand of the ash (25) (26) (30) which in turn affects the workability, strength and durability of the final product.

In view of the above and the fact that the material was obtained from a single source and selected on a particle size basis, both materials were subjected to particle size analysis involving a combination of the techniques contained in B.S. 812 (49) and B.S. 1377 (50) which was a sedimentation method based upon Stokes' Law.

4.3.2 Tests and materials' properties

For brevity a description of the tests carried out is omitted however sufficient tests were made to comply with a) and b). These are tabulated below. Brief descriptions and the relevant British Standards are also included.

Table 4.3.2 A

Summary of Tests carried out on constituent materials

Test carried out denoted thus ✓	Cement	Pozzolan 1	Pozzolan 2	Fine Aggregate	Coarse Aggregate	B.S. No.	Description
Specific surface	✓	✓	✓	-	-	BS 12 BS 3892	Lee & Nurse & (47 Rigden Cell. (48)
Specific gravity	✓	✓	✓	✓	✓	BS 12 BS 3892	Density bottle.
Sieve Analysis (1)	-	✓	✓	✓	✓	BS 812	Nest of sieves with mechanical vibration. (49)
Sieve Analysis (2)	-	✓	✓	-	-	BS 1377	Sedimentation method. (50)
Consistency	✓	✓	✓	-	-	BS 12	Vicat needle. (47)
Moisture absorption	-	-	-	✓	✓		
Chemical Analysis	✓	✓	✓	-	-	BS 3892	Sulphite content. (48)
Ignition Loss	✓	✓	✓			BS 3892	Weight loss in muffle furnace. (48)

Table 4.3.2. B Description and Source of Constituents

Constituent	Description	Source
Cement	Ordinary Portland	Ketton.
Pozzolan 1	Treated p.f.a. *	Fiddler's Ferry 'B' Power Station via Pozzolanic Pty Ltd, Chester.
Pozzolan 2	Untreated p.f.a.	Fiddler's Ferry 'B' Power Station via Pozzolanic Pty Ltd, Chester.
Fine Aggregate	Zone 2 sand	Hoveringham, Finningley.
Coarse Aggregate	20mm graded gravel	Hoveringham, Finningley.
Water	Tap water (potable)	Yorkshire Water Authority.

* Material in accordance with Agrément certificate No. 75/283. (51)

Table 4.3.2 C Properties of Constituents

Property \ Constituent	Cement (O.P.C.)	Pozzolan 1 (selected p.f.a.)	Pozzolan 2 (unselected p.f.a.)	Fine Agg. (Zone 2 sand)	Coarse Agg. (20mm graded gravel)	Water	Units
Specific gravity	3.16	2.22	1.99 *	2.68	2.66	1.00	-
Specific surface	292	276 Zone B	189 * Zone A	-	-	-	m^2/kg
% passing (% retained) on 150μm sieve	99 (1)	99 (1)	91 * (9)	1 (99)	0 (100)	-	%
% passing (% retained) on 44μm sieve	70 (30)	93 (7)	48 * (52)	0 (100)	0 (100)	-	%
Standard consistency	27	25	38	-	-	-	%
Moisture absorption (S.S.D.)	-	-	-	2.0	1.5	-	%
Sulphate content as SO_3	0.44	2.04	2.33	-	-	-	%
Ignition loss	1.6	4.4	6.8 *	-	-	-	%
Moisture content	-	0.5	0.5	-	-	-	%

* non-compliance with Physical or Chemical requirements of Agrément Certificate No. 75/283, A.S. 1129 and ASTM C 618 (see T.4.3.2 D)

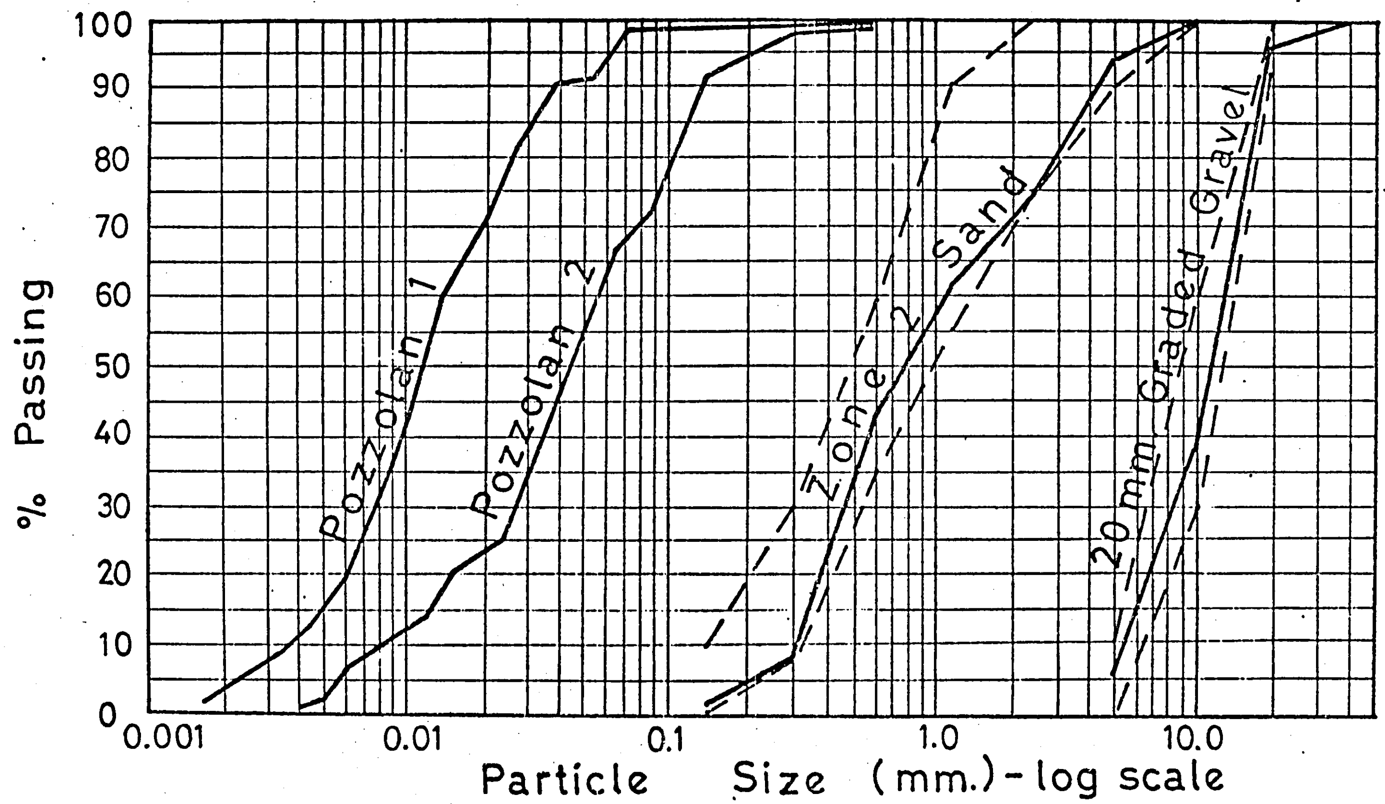
Table 4.3.2 D Typical standard specifications for p.f.a. in concrete (52)

Chemical

Property / Standard	S_iO_2 + Al_2O_3 + Fe_2O_3 min %	Mg O max %	SO_3 max %	Loss on ignition max %	Available alkalis (Na_2O) max %	Moisture content max %
Agrément Certificate No. 75/283	-	-	-	6.5	-	-
Australia A.S. 1129	-	-	2.5	8.0	-	1.5
U.K. B.S. 3892	-	4.0	2.5	7.0	-	1.5
U.S.A. A.S.T.M. C 618	70	-	5.0	12.0	1.5	3.0

Physical

Property / Standard	Retained on 150μm sieve (max %)	Retained on 44μm sieve (max %	Specific Surface - Lea and Nurse (m^2/kg)	Density kg/m^3
Agrément Certificate No. 75/283	2.5	12.5	Zone B, 275 - 425	2,000 (min)
Australia A.S. 1129	10	50	-	-
U.K. B.S. 3892	-	-	Zone A 125 - 275 B 275 - 425 C 425	-
U.S.A. A.S.T.M. C 618	-	20	325 (min)	-



G.4.3.2 GRADING CURVES

4.3.3 Observations

4.3.3.1 Properties of constituents and compliance

(Table 4.3.2 C, Table 4.3.2 D)

Pozzolan 2 (untreated p.f.a.) fails to comply with the requirements of the following specifications.

Specification	Compliance failure
Agrément Certificate	Ignition loss, specific surface.
Agrément Certificate	% retained on 150μm sieve.
Agrément Certificate	% retained on 44 μm sieve.
A.S. 1129	% retained on 44 μm sieve.
A.S.T.M. C 618	% retained on 44 μm sieve.
A.S.T.M. C 618	Specific surface.

Pozzolan 1 (treated p.f.a.) from the same source as Pozzolan 2 however complies comfortably with all the requirements listed in Table 4.3.2 D.

4.3.3.2 Grading curves (G. 4.3.2)

Pozzolan 1 and 2

The particle size distribution indicates that Pozzolan 2 is a coarser material than Pozzolan 1 although paradoxically the standard consistency test (Table 4.3.2 C) indicates that the former (P 2) has a higher water demand (38%). The author considers that this is probably due to the influence of particle shape causing P 2 to have much higher internal friction than P 1, accompanied with higher absorption by the carbonaceous material (6.8% for P 2 compared with 4.4% for P 1). The author also noted that P 2 was distinctly less cohesive than P 1.

The Pozzolan 1 and 2 p.f.a.s are considerably finer than the fine aggregate. The grading of P 1 is reasonably uniform but less so at the coarse end of the curve where the grading could be affected by the selection process. The grading of P 2 is reasonably uniform throughout the particle size range.

Fine aggregate and coarse aggregate

Both of these materials conform within the specification limits of B.S. 882 and 1201, 1965 (53) although the sand is a relatively coarse Zone 2. The gradings are reasonably uniform in each case.

5.0 Mix Design

5.1.0 Introduction

The process of mix design involves the economic combination of concrete materials to give the desired physical properties in terms of workability, strength and durability.

This sentence is merely a statement embodying the essentials of the mix design process and one must move from here to choose the particular materials which comply with the specification laid down.

There are two principal ways in which this can be done namely by the prescribed mix and designed mix method. These will be briefly discussed.

5.1.1 Prescribed mixes (29)

In this method the quantities or proportions of mix constituents are specified by the consumer with an expectation, allowing for normal variability of materials, that the resulting concrete strength will be in excess of the figure required; assuming that normal workability requirements are adhered to. Using this method, however, the responsibility for strength falls upon the specifier and strength is not used as a criterion by which acceptance of prescribed mixes is judged.

Examples of prescribed mixes are found in the following:-

CP 110	Table 50 (29)
CP 114	(known as standard mixes) *
CP 116	(known as standard mixes) *

5.1.2 Designed mixes (29)

In this approach the consumer specifies the required strength, workability and sometimes durability of the concrete. It is the producers task to manufacture concrete which complies with this specification. A margin for variability of materials and quality control is allowed by the producer in order that a very small proportion (for example 5%) of the concrete produced is likely to be below the characteristic strength or grade required by the consumer.

The methods which the producer uses to produce concrete of the required strength are numerous but most methods incorporate an allowance for cement type, aggregate characteristics, in terms of aggregate grading and the regularity of coarse aggregate and an overall allowance for quality control in the context of the production conditions.

The initial water, cement and aggregate contents (or ratios) are usually obtained from charts or tables and a trial mix manufactured. The trial mix is then tested for workability and strength and adjustments are made to mix proportions, if necessary, to comply with requirements.

* see Miscellaneous References.

At the beginning of the project two such methods were widely used in the U.K., namely:-

i) Road Note 4 - Design of concrete mixes. R.R.L. (54)

ii) The Basic Mix Method - C. & C.A. (55)

Since the experimental portion of this research was completed a third method has been published to supersede Road Note 4 (which was primarily produced for concrete pavements) namely:-

'Design of normal concrete mixes' by D.O.E., C.& C.A. B.R.E. and T.R.R.L. (56)

5.1.3 Design methods for Control Mix previously used

Previous work in the field of p.f.a. concretes appeared to make use of standard mixes available. Goodridge and Jackson (15) used 1:2:4, 1:1½:3 type standard mixes as controls and replaced fine aggregate and cement in accordance with their standard procedure. The work by Venuat et al (18) was conducted using 1:3 mortar specimens and similarly with Timms and Grieb.(12)

Only Cannon (22) appears to adopt a comprehensive mix design approach for p.f.a. concretes although this has the limitation that it is based on material from a limited source.

Pozzolanic Pty Ltd used strength/workability designed mixes which had been used for a considerable period but the author felt that the durability aspect had not been thoroughly tested.

After considerable consultation with organisations such as C.E.G.B. and B.R.E., the author decided to draw up a list of requirements for the control mix and consider these in the light of existing options, mentioned previously.

These are considered in the next sub-section.

5.2.1 Requirements of Control Mix

These can be summarised as follows:-

i) It should provide adequate strength at high water:cement ratios and high p.f.a. contents to ensure that all strengths lie within the working range of the testing apparatus at early ages and also to facilitate the stripping of moulds after 24 hours.

ii) The Cement/Fine Aggregate/Coarse Aggregate ratios should be sufficient to ensure satisfactory workability characteristics throughout the water:cement ratio range.

iii) Sufficient cement content to ensure adequate resistance against chemical attack.

iv) A medium strength mix likely to be representative of that used throughout the construction industry.

5.2.2 Choice of Control Mix

The initial choice was between a designed and prescribed mix approach.

The author felt that although Road Note 4 featured in some of the previous work on p.f.a. concretes (16) (54) (57), its exclusive dependence on the slump and compacting factor as workability tests and its bias towards concrete pavements limited its application to this work. Road Note 4 has since been superseded as mentioned previously.

For specified strength and workability, it was felt that the Basic Mix Method (55) was applicable but in common with Road Note 4 it utilised the slump and compacting factor tests and there was no provision for durability. It was further considered that the relatively low cement contents in mixes designed from purely strength/workability considerations would result in very weak concretes at high water:cement ratios and high cement replacement which would not comply with i) above and limit the range of cement replacements to be explored.

As a result of the above the author felt that a prescribed mix would more successfully fulfil requirements i) - iv) and further that the prescribed mixes in Table 50 of C.P. 110 would provide an excellent base from which to start in that an allowance is made for durability in terms of minimum cement content. (29)

The current method of specifying mix proportions in terms of kg/m^3 instead of cement/fine aggregate/coarse aggregate ratios is used here and presents a less confusing picture to the producer especially when another ingredient is introduced such as p.f.a.

In addition, the author had seen little data from concrete produced using Table 50 and considered that useful information regarding the 'minimum cement content' might be obtained with a view to replacing part of the O.P.C. with p.f.a. and measuring the effect upon resistance to chemical attack. (29)

Most of the previous work done on p.f.a. concretes had utilised medium strength mixes, therefore the author decided that in order that useful comparisons might later be drawn that the control mix should be a medium strength/workability concrete. This would also allow the author to use cement replacements resulting in a reduction in the O.P.C. content well below the 'minimum cement content' level. (29)

Prescribed mix Grade 20, Table 50 C.P. 110 with medium workability was considered the most suitable for this purpose. Details are tabulated below.

Table 5.2.2. Prescribed mix Grade 20 and variants

Nominal characteristics		Nominal mix quantities				Nominal proportions (by wt.)
Strength	Workability	Water	Cement	Fine Agg.	Coarse Agg.	O.P.C./F.A./C.A.
Grade	Slump (mm)	kg/m^3	kg/m^3	kg/m^3	kg/m^3	
-	Zero	128	320	630	1170	
20	25 - 75	160	320	630	1170	1 : 2.0 : 3.6
-	Collapse	192	320	620	1170	

Preliminary tests carried out using the proportions set out above corresponding to 25-75 mm slump produced compressive strengths ranging from 44.5 N/mm^2 to 63.2 N/mm^2 at 28 days with water contents of 160 kg/m^3 and 135 kg/m^3 respectively.

It was decided that the water content of 160 kg/m^3 produced a strength more appropriate to that of a grade 20 concrete and this was adopted as the control. In order to provide more comprehensive information high and low workability variants of the control were included as base mixes.

For the sake of numerical simplicity the author decided to use the water contents listed above which corresponded to water:cement ratios of 0.40 (zero), 0.50 (25-75 mm), 0.60 (Collapse) where slump figures are in brackets.

These three mixes formed the bases of the subsequent mix programme and thereafter virtually all p.f.a. mixes were manufactured using one of the three water contents listed above. It must be emphasised that wherever 'W/C ratio' is used this refers to the W/C ratio of the base (O.P.C.)mix and NOT of the p.f.a. mix to which it is assigned. Put another way, (with one exception) only three different water contents were used throughout the whole mix programme.

Much of the previous work on p.f.a. concretes had been done on the basis of equal workability. The author felt this could be misleading for two reasons firstly (a) because a single workability test could not measure comprehensively the workability of concrete and (b) in using the constant workability criterion it was often difficult to isolate variables, for example water content and cement/p.f.a. content could be changed simultaneously.

The author considered that in adopting a 'grid' approach and measuring the effects of cement and fine aggregate replacement with p.f.a. a more objective view could be taken of the use of p.f.a. in concrete.

5.3.1 Incorporation of p.f.a. in concrete

P.f.a. can be incorporated in concrete in several ways and these are listed below:-

i) Cement replacement by volume of p.f.a.

ii) Cement replacement by weight of p.f.a.

iii) Fine aggregate replacement by weight of p.f.a.

iv) Fine aggregate replacement by volume of p.f.a.

v) Cement and fine aggregate replacement by equivalent weight of p.f.a.

vi) Cement and fine aggregate replacement by equivalent volume of p.f.a.

vii) Cement replacement by weight and fine aggregate replacement by volume of p.f.a.

viii) Cement/p.f.a. ratio for equivalent water demand.

The author's choice of the method used in this work was influenced by the following factors:-

i) The comparative water demands of cement, p.f.a. and fine aggregate.

ii) The range of water contents of the concretes being tested.

iii) The volumetric yield of the ingredients being used.

iv) The relative specific gravities of the constituents.

The previous method of replacement used by Goodridge and Jackson (15) was considered by the author but since this method was orientated towards p.f.a./cement ratios rather than p.f.a., cement contents the author considered this method not easily compatible with that of the weight per unit volume basis of Table 50. Further, the optimum p.f.a./cement ratio propounded was not universally applicable. (10) Calculation of yield would also be more complicated since the weight replacement of cement resulted in a net volumetric increase owing to the differences between specific gravity of cement and p.f.a.

In order to facilitate the calculation of concrete yields so that economics of replacements could be determined, combined with the desire to keep as close as possible to the weight per unit volume method of specifying constituents for concrete, the author decided to adopt method (vi) Cement and Fine Aggregate replacement by equivalent volume of p.f.a.

5.3.2 Application of replacement technique

Mixes are most accurately and conveniently batched by weight, therefore the weight of p.f.a. (M_{pc}) required to replace an equal volume of cement was achieved as follows:-

Let V_c = Volume of cement to be replaced.

V_{pc} = Volume of p.f.a. to be substituted.

M_c = Weight of cement to be replaced.

M_{pc} = Weight of p.f.a. to be substituted.

ρc = Solid density of cement.

ρp = Solid density of p.f.a.

Then 1) $V_c = \frac{M_c}{\rho c}$

and

2) $V_{pc} = \frac{M_{pc}}{\rho p}$

But $V_c = V_{pc} = \frac{M_c}{\rho c} = \frac{M_{pc}}{\rho p}$

3) $\therefore M_{pc} = \frac{\rho p}{\rho c} \cdot M_c$

$\frac{\rho p}{\rho c} = \frac{\text{Relative density of p.f.a.}}{\text{Relative density of cement}}$ = p.f.a./cement Replacement Factor

By similar reasoning

where V_a = Volume of fine aggregate to be replaced.

V_{pa} = Volume of p.f.a. to be substituted.

M_a = Weight of fine aggregate to be replaced.

M_{pa} = Weight of p.f.a. to be substituted.

ρa = Solid density of fine aggregate.

ρp = Solid density of p.f.a.

4) $M_{pa} = \frac{\rho p}{\rho a} \cdot M_a$

where

$\frac{\rho p}{\rho a} = \frac{\text{Relative density of p.f.a.}}{\text{Relative density of fine aggregate}}$ = p.f.a./fine aggregate Replacement Factor

Using the above principals and using relative densitites *
from T. 4.3.2 C a table of replacement factors can be drawn up for Pozz. 1, Pozz. 2, Cement and Fine Aggregate as follows:

Table 5.3.2 Relative Densities and Replacement Factors

Material	Relative Density	Materials - relative density ratio	Replacement Factor
Cement	3.16	$\frac{\text{Pozz. 1}}{\text{Cement}}$	0.700
Fine Agg.	2.68	$\frac{\text{Pozz. 2}}{\text{Cement}}$	0.630
Pozz. 1	2.22	$\frac{\text{Pozz. 1}}{\text{Fine Agg.}}$	0.830
Pozz. 2	1.99	$\frac{\text{Pozz. 2}}{\text{Fine Agg.}}$	0.740

5.3.3 Replacement levels for p.f.a.

Typical cement replacement levels previously used for p.f.a. concretes ranged from 0 to 90% but in the majority of cases the effective replacement levels (to maintain adequate strength) was between 20 and 30% (by weight). Only Venuat (18) appears to have reached 90% cement replacement and this using a 1:3 mortar mix.

* numerically equal to Specific Gravity.

Fine aggregate replacement as a technique is less frequently encountered but Goodridge and Jackson (15) appear to have reached 50% (by volume) without adverse effect.

Australian practice utilises a 20% cement replacement by weight and 3% fine aggregate replacement by volume (58) which conceals a higher effective fine aggregate replacement on a volume basis (or p.f.a. inclusion) because of the lower relative density of p.f.a. than cement.

The cement replacement levels to be used by the author were determined chiefly by the effect upon strength (up to 91 days) and as the result of surveying previous work (12). From this it was decided that 50% cement replacement by volume was the maximum commercially viable level of replacement.

On the basis of the above the economic level of fine aggregate replacement was 35%; taking into account the relative costs of materials as follows:-

cement > p.f.a. > fine aggregate

Applying the replacement factors, as previously deduced, to the required levels of cement and fine aggregate replacement in the control mix (see Table 5.2.2) gives the following quantities of p.f.a. (Pozz. 1 and Pozz. 2) per m^3, based on the nominal figures in CP 110, Table 50. (Tables 5.3.3 A and B)

For combined cement and fine aggregate replacement using Pozz. 1 and Pozz. 2 details are set out in Tables 5.3.3 C and D.

At maximum replacement level i.e. at 50% cement and 35% fine aggregate replacement the weight of p.f.a. (293 and 263 per m^3) approaches that of the cement in the control mix (320 kg/m^3)

Further details of the respective quantities of constituent materials per m^3 are given in Appendix I.

Table 5.3.3 A Cement replacement (C.R.) (kg/m^3)*

% Cement replacement	0	10	20	35	50	Replacement Factor
Cement replaced (kg)	0	32	64	112	160	
Pozz. 1 (kg) substituted	0	23	45	79	113	0.700
Pozz. 2 (kg) substituted	0	20	40	70	101	0.630

Table 5.3.3 B Fine aggregate replacement (F.A.R.) (kg/m^3)*

% Fine Agg. replacement	0	5	15	25	35	Replacement Factor
Fine Agg. replaced (kg)	0	32	95	158	221	
Pozz. 1 substituted (kg)	0	26	76	129	181	0.830
Pozz. 2 substituted (kg)	0	23	69	115	162	0.740

Table 5.3.3 C Combined F.A.R. and C.R. with Pozz. 1 (kg/m^3)*

% C.R. \ % F.A.R.	0	5	15	25	35
0	0	26	76	129	181
10	23	48	99	152	204
20	45	71	122	174	226
35	79	105	156	208	259
50	113	139	190	242	293

Table 5.3.3 D <u>Combined F.A.R. and C.R. with Pozz. 2 (kg/m³)*</u>

% C.R. \ % F.A.R.	0	5	15	25	35
0	0	23	69	115	162
10	20	43	89	135	182
20	40	63	109	156	202
35	70	94	140	186	232
50	101	124	170	216	262

* Quantities based on Table 50, CP 110.

5.4 Explanation of Nomenclature

In order to facilitate the recording of results and final collation of data the following referencing system was devised.

5.4.1 Mix No.

This refers to the chronological position of the mix and precedes the mix code, to be described below. Mix No. 1 precedes No. 10 which in turn precedes No. 116 etc and embraces both O.P.C and O.P.C./p.f.a. mixes.

5.4.2 Mix Code

This describes the mix more specifically in terms of level of cement/fine aggregate replacement, pozzolana used and water content. A six and eight figure code describes O.P.C. and O.P.C./p.f.a. mixes respectively as follows:-

5.4.3 Figures 1 - 4 refer to type of mix i.e. O.P.C. or O.P.C./p.f.a. and level of cement replacement.

e.g. 00 ≡ 0% cement replacement (no p.f.a.)

P 110 ≡ 10% cement replacement with Pozz. 1

i.e. P1 indicates that the mix contains p.f.a. type Pozzolan 1 at a replacement level of 10% by weight of cement with an equivalent volume of P 1.

5.4.4 Figures 5 - 6 refer to the level of fine aggregate replacement.

e.g. 00 ≡ 0% fine aggregate replacement.

15 ≡ 15% fine aggregate replacement with p.f.a. (type denoted by Figures 1 and 2).

5.4.5 Figures 7 - 8 refer to the water content of the mix in terms of the water:cement ratio of the O.P.C. base mix.

e.g. 50 ≡ water content of 160 kg ≡ 0.50

where 0.50 ≡ water:cement ratio of O.P.C. base mix.

5.4.6 Typical mixes and mix codes

Example 1

A mix with the same basic proportions of cement, fine aggregate and coarse aggregate as control but with 10% cement and 15% fine aggregate replacement with Pozz. 1 and water content of 160 kg ≡ O.P.C. base mix water:cement ratio ≡ 0.50 is coded as follows:-

P 110/15/50

A similar mix but with Pozz. 2 instead of Pozz. 1 is coded P 210/15/50.

Example 2

A mix with 0% cement and 0% fine aggregate replacement and water content = 160 kg ≡ water:cement ratio (O.P.C. base mix) of 0.50 is denoted

00/00/50 (which is the 'Control')

Example 3

A mix with 0% cement, 5% fine aggregate replacement with Pozz. 2, water content of 128 kg ≡ O.P.C. base mix, water:cement ratio of 0.40, is denoted

P 200/05/40

5.4.7 Water:cement ratio

Subsequently, the author will use the following notation for water:cement ratios.

W/C = water:cement ratio (i.e. where cement is O.P.C.) by weight.

$^{W}/_{C_c}$ (i.e. constant water volume) = water:cement ratio by weight of O.P.C. base mix.

In the case of base and control mixes

$$^{W}/_{C} = {}^{W}/_{C_c}$$

Examples 1 - 3 from above, tabulated below will further illustrate this point.

Table 5.4.7

Examples 1 - 3 (mix code)	$^{W}/_{C}$	$^{W}/_{C_c}$	Water content (kg)
P 110/15/50	0.55	0.50	160
00/00/50	0.50	0.50	160
P 200/05/40	0.40	0.40	128

5.5 Concrete Yield

The prescribed mixes in Table 50, CP 110 contain estimated weights of constituents necessary to produce 1 m^3 of fully compacted concrete. These are based upon the relative densities of the constituents (see Cl 5.3.2) assuming that sufficient volume of water has been added to give the specified workability, in this case 25 - 75 mm slump.

The author found that using the range of water contents outlined in Table 5.2.2 of this text combined with the nominal quantities of constituents corresponding to Grade 20, medium workability concrete from Table 50, CP 110, the volumetric yields at each water content could be calculated. The author used the values for solid densities calculated by himself (see Table 4.3.2 C).

By multiplying the nominal constituent weights by the reciprocal of the true volumetric yield the actual weights of constituents per m^3 can be determined at each water content.

This was calculated as follows:-

$$\text{Vol. of fresh concrete} = V\ \text{air} + V\ \text{water} + V\ \text{cement} + V\ \text{f.a.} + V\ \text{c.a.}$$

For water content = 128 kg,

and vol. of air = 0.005 m^3 *

$$\text{Vol. of fresh concrete} = 0.005 + \frac{128}{1000} + \frac{320}{3160} + \frac{630}{2680} + \frac{1170}{2660} = \underline{\underline{0.909}}\ m^3$$

$$\therefore \text{ Yield factor} = \frac{1}{0.909} = 1.10$$

The Yield factors for other water contents were calculated similarly but the author found that for water contents higher than 128 kg the volume of air was negligible.*

Table 5.5 Yield factors for O.P.C. base mixes

Water content (kg)	128	160	192	224
Water/cement ratio	0.40	0.50	0.60	0.70
Volume of air (m^3)	0.005*	-	-	-
Volume of water (m^3)	0.128	0.160	0.192	0.234
Volume of cement (m^3)	0.101	0.101	0.101	0.101
Volume of f.a. (m^3)	0.235	0.235	0.235	0.235
Volume of c.a. (m^3)	0.440	0.440	0.440	0.440
Total volume (m^3)	0.909	0.936	0.968	1.00
Yield factor	1.100	1.068	1.033	1.00

* deduced from fresh concrete density in conjunction with Compacting Factor Test.

5.6 Cost

The previous section described the techniques used for cement and fine aggregate replacement using Pozzolan 1 and Pozzolan 2 and also the method of calculating mix yields based on O.P.C. mixes. These concepts will be developed further with respect to the cost of concrete (constituents only) produced.

5.6.1 General expression

Included in the following table are prices (as at June 1974), weights, densities of constituents together with symbols used in the subsequent derivations.

Table 5.6.1

Description	Cost - £/tonne		Weight (kg)	Density tonne/m^3
	Actual	Symbol		
Cement (O.P.C.)	9 - 50	Pc	Wc	3.16
P 1 or P 2 repl. cement	-	P_{pc}	W_{pc}*	-
P 1 or P 2 repl. f.a.	-	P_{pa}	W_{pa}*	-
Pozzolan 1	5 - 50	P_{p1}*	W_{p1}	2.22
Pozzolan 2	3 - 00	P_{p2}*	W_{p2}	1.99
Fine aggregate	1 - 50	Pa	Wa	2.68
Coarse aggregate	1 - 50	P_A	W_A	2.66
Total		P_T	-	-

* $Wp = W_{pc} + W_{pa}$ and $Pp = P_{p1}$ or P_{p2} .

The author felt that the derivation of a general expression for the cost of concrete (P_T) in terms of the constituent materials and their relative proportions within the mix would be useful and is developed as follows:

The general form of the expression is as follows.

1) $P_T = Wc\ Pc + W_p\ P_p + Wa\ Pa + W_A\ P_A$ .... 1)

where the terms used are stated in Table 5.6.1. The cost of water is assumed at zero.

5.6.2 Cement and Fine aggregate replacement

If C_R = % cement replacement by equal volume of p.f.a.

F_R = % fine aggregate replacement by equal volume of p.f.a.

Using the control mix proportions in Table 5.2.2.

$$Wc = 0.320\left(1 - \frac{C_R}{100}\right) \text{ tonne} \quad \ldots\ldots\ldots\ldots \quad 2)$$

$$Wa = 0.630\left(1 - \frac{F_R}{100}\right) \text{ tonne} \quad \ldots\ldots\ldots\ldots \quad 3)$$

From section 5.3.2 we have seen that

$$M_{pc} = \frac{\rho p}{\rho c} Mc \qquad \therefore W_{pc} = \frac{\rho p}{\rho c} Mc$$

But by definition $Mc = \frac{C_R}{100}\,0.320.$

$$\therefore W_{pc} = \frac{\rho p}{\rho c} \cdot \frac{C_R}{100}\ 0.320 \quad \text{and rearranging}$$

$$W_{pc} = \rho p \cdot \frac{C_R}{100}\ \frac{0.320}{\rho c}$$

From Table 5.5 $\frac{0.320}{\rho c} = 0.101\ m^3.$

$$\therefore W_{pc} = \underline{0.101 \cdot \rho p \cdot \frac{C_R}{100}} \quad \ldots\ldots\ldots\ldots \quad 4)$$

By similar reasoning using

$$M_{pa} = \frac{\rho p}{\rho a} \cdot Ma \qquad \text{(Table 5.3.2)}$$

and substituting $\frac{0.630}{\rho a} = 0.235\ m^3$ (Table 5.5)

$$\therefore W_{pa} = \underline{0.235\ \rho p\ \frac{F_R}{100}} \quad \ldots\ldots\ldots\ldots \quad 5)$$

Therefore since $W_p = W_{pc} + W_{pa}$ .... 6)

Substituting 4) and 5) in 6)

gives $$W_p = 0.101 \cdot \rho p \frac{C_R}{100} + 0.235 \rho p \frac{F_R}{100}$$

or $$W_p = \rho p \left(0.101 \frac{C_R}{100} + 0.235 \frac{F_R}{100} \right) \ldots \qquad 7)$$

Substituting 2), 3) and 7) in 1)

$$P_T = 0.320 \left(1 - \frac{C_R}{100}\right) Pc + 0.630 \left(1 - \frac{F_R}{100}\right) Pa$$
$$+ \rho p \left(0.101 \frac{C_R}{100} + 0.235 \frac{F_R}{100}\right) + W_A P_A.$$

From Table 5.2.2 $W_A = 1.17$ tonne.

$$\therefore \quad P_T = 0.320 \left(1 - \frac{C_R}{100}\right) Pc + 0.630 \left(1 - \frac{F_R}{100}\right) Pa$$
$$+ \rho p \left(0.101 \frac{C_R}{100} + 0.235 \frac{F_R}{100}\right) P_p + 1.17\, P_A \ldots \qquad 8)$$

For Pozzolan 1 this expression becomes

$$P_{T1} = 0.320 \left(1 - \frac{C_R}{100}\right) Pc + 0.630 \left(1 - \frac{F_R}{100}\right) Pc \qquad 9)$$
$$+ 2.22 \left(0.101 \frac{C_R}{100} + 0.235 \frac{F_R}{100}\right) P_{p1} + 1.17\, P_A \qquad 9)$$

and for Pozzolan 2

$$P_{T2} = 0.320\left(1 - \frac{C_R}{100}\right)Pc + 0.630\left(1 - \frac{F_R}{100}\right)Pa \quad .. \quad 10)$$

$$+ 1.99\left(0.101\frac{C_R}{100} + 0.235\frac{F_R}{100}\right)P_{p2} + 1.17\,P_A \quad 10)$$

5.6.3 Indexed Prices

By indexing these prices in terms of the cost of a particular constituent e.g. cement, it is possible to draw up a family of curves indicating the economic 'cut off' point for cement/fine aggregate replacement with p.f.a. However, for brevity the author has omitted this and included instead a table of concrete costs (constituents only) in terms of cement/fine aggregate replacement and constituent prices as at June 1974 (Sheffield area).

This table has been compiled by applying equations 9) and 10) to Tables 5.5 and 5.6.1.

Table 5.6.3 Costs of concrete - based on Table 50, CP 110

pfa	% F.A.R. / % C.R.	0	5	15	25	35	
Pozzolan 1	0	5.75	5.85	6.05	6.20	6.40	
	10	5.55	5.65	5.85	6.05	6.25	
	20	5.40	5.50	5.70	5.85	6.05	
	35	5.10	5.20	5.40	5.60	5.80	Dearer than control
	50	4.85	4.95	5.15	5.30	5.50	Cheaper than control
pfa	**%F.A.R. / % C.R.**	**0**	**5**	**15**	**25**	**35**	
Pozzolan 2	0	5.75	5.75	5.80	5.85	5.90	Dearer than control
	10	5.50	5.50	5.55	5.65	5.65	Cheaper than control
	20	5.25	5.30	5.35	5.40	5.40	
	35	4.90	4.90	4.95	5.00	5.05	
	50	4.55	4.55	4.60	4.65	4.70	

Costs in £/m^3 (nominal) to nearest 0.05.

5.6.4 True cost adjusted for yield

The above table is based upon mix proportions for Grade 20 concrete, medium workability in Table 50, CP 110. To obtain the true cost per cubic metre these values should be multiplied by the yield factors in the Table below.

Table 5.6.4 Yield Factors

Water content	Water:cement ratio	Yield factor
kg	O.P.C. base mix	± 0.005
	$^{W}/_{C_c}$	
128	0.40	1.10
160	0.50	1.07
192	0.60	1.03
224	0.70	1.00

CHAPTER 6

MIXING AND TESTING PROGRAMME

6.0 Mixing and Testing Programme

6.1. Introduction

Previous sections have dealt with the selection of workability, strength and durability testing methods and the types of mixes to which they will be applied.

This section will elaborate on particular aspects of the tests conducted, especially where non-standard testing methods are used or where there is a deviation from British Standard practice.

The nomenclature and testing programme will also be described in this section.

6.2 Mixes to be tested

The range of cement and fine aggregate replacements to be investigated are listed in Table 5.3.3. A - D, which are reproduced here. In addition, the author proposed to investigate the behaviour of these mixes with different water contents. A large proportion of the mixes were manufactured using three different water contents (see Table 5.5.)

Assuming all of the above was comprehensively investigated this would have totalled 150 mixes for the two pozzolanas, Pozz. 1 and Pozz. 2.

However, to conform within the limits of the time schedule, the author decided upon a mix programme which optimised on the following:-

i) The most efficient use of laboratory resources.

ii) Using the minimum number of mixes necessary to determine the economic limits of cement and fine aggregate replacement with Pozz. 1 and Pozz. 2 consistent with maintaining adequate workability, strength and durability as measured relative to the control mix (00/00/50).

For details of the actual mixes selected for investigation from the proposed range see Appendix I.

In order to comply with the above, the author chose initially to work to the outer limits of the ranges before converging towards the optimum replacement levels.

Table 5.3.3A Cement replacement (C.R.) (kg/m^3)*

% Cement replacement	0	10	20	35	50	Replacement Factor
Cement replaced (kg)	0	32	64	112	160	
Pozz. 1 (kg) substituted	0	23	45	79	113	0.700
Pozz. 2 (kg) substituted	0	20	40	70	101	0.630

Table 5.3.3 B Fine aggregate replacement (F.A.R.) (kg/m^3)*

% Fine Agg. replacement	0	5	15	25	35	Replacement Factor
Fine Agg. replaced (kg)	0	32	95	158	221	
Pozz. 1 substituted (kg)	0	26	76	129	181	0.830
Pozz. 2 substituted (kg)	0	23	69	115	162	0.740

Table 5.3.3 C Combined F.A.R. and C.R. with Pozz. 1 (kg/m^3)*

% C.R. \ % F.A.R.	0	5	15	25	35
0	0	26	76	129	181
10	23	48	99	152	204
20	45	71	122	174	226
35	79	105	156	208	259
50	113	139	190	242	293

Table 5.3.3 D Combined F.A.R. and C.R. with Pozz. 2 (kg/m^3)*

% C.R. \ % F.A.R.	0	5	15	25	35
0	0	23	69	115	162
10	20	43	89	135	182
20	40	63	109	156	202
35	70	94	140	186	232
50	101	124	170	216	262

* Quantities based on Table 50, CP 110.

6.3 Control mixes (00/00/50)

The limited storage facilities of the laboratory necessitated the delivery of several consignments of materials (cement, fine aggregate, coarse aggregate) throughout the period of the investigation, (although Pozz. 1 and Pozz. 2 were delivered in a single consignment). To ensure the consistency of the basic ingredients and laboratory practice, control mixes (Mix Code 00/00/50) were manufactured at intervals throughout the mixing programme.

At the end of the mixing programme the results of controls were averaged and standard deviations and coefficients of variation were determined to establish the characteristics of the 'parent' population. All p.f.a. mix results were considered in the context of the following:-

i) mean control strength ($\bar{x}$)

ii) control limits set at 1.64s* from the mean (equivalent to 10% percentiles of a normal population).

6.4. Manufacture and Testing of Specimens

6.4.1 Quantities of materials

In order to produce sufficient quantities of fresh concrete for the testing programme (see Table 5.7) it was found necessary to divide the mix into two batches to keep within the mixer capacity. The quantities of materials in each batch correspond to the mix proportions in Table 5.3.3 divided by 11.73.

6.4.2 Moisture contents

Moisture contents of cement and Pozzolan 1 and 2 were not monitored continuously but were checked periodically. Variation from the values quoted in Table 4.3.2.D was insignificant.

Moisture content of coarse and fine aggregate was determined for each batch using the 'Speedy' moisture meter with an appropriate adjustment being made to each batch

* s = estimated standard deviation of normal population.

weight to compensate for the water content of the aggregate.

6.4.3 Batching

All mixes were weight batched in the mixer pan in a symmetrical layer pattern as follows:

Coarse Aggregate, Fine Aggregate, Pozz. 1 or 2, Cement, Pozz. 1 or 2, Fine Aggregate, Coarse Aggregate; the relative quantities depending on the mix type.

Avery scales were used for the batching, calibrated to an accuracy of ±0.05 kg. (250 kg maximum load)

6.4.4 Mixing

Mixing was carried out in a Liner Cumflow horizontal mixer. Semi-dry materials were mixed for a period of 1 minute. Water was then added and mixing continued for at least a further 2 minutes. The total mixing time was 3 minutes.

6.4.5 Workability tests

All workability tests were carried out in accordance with BS 1881, Part 2, but for the Compacting Factor test a vibrating table was used to compact concrete in the cylinder.

The times after mixing at which each test was carried out were as follows:

Test	Time after mixing
Slump	2 minutes
Compacting Factor	4 minutes
VeBe	6 minutes
2 Point Test	8 minutes

6.4.6 2 Point Test (see Plate 1)

To minimise the variation of machine performance under load, the Hobart AE 200 mixer was allowed to warm up for 30 minutes before each test. The duration of each test was approximately 2 minutes.

6.4.7 All tests - dubious results.

In the case of dubious results being recorded, the test was repeated.

6.4.8 Specimen manufacture (See Table 6.5.7)

All specimens were manufactured in accordance with BS 1881, Part 3 using a vibrating table for compaction. The appropriate compaction time was determined from observation of the specimen surface for rising air bubbles. When these ceased, compaction was considered complete. Compaction times varied between 1 minute and 2 minutes for cubes and beams and between 1 minute and 3 minutes for cylinders; times increasing for decrease in workability.

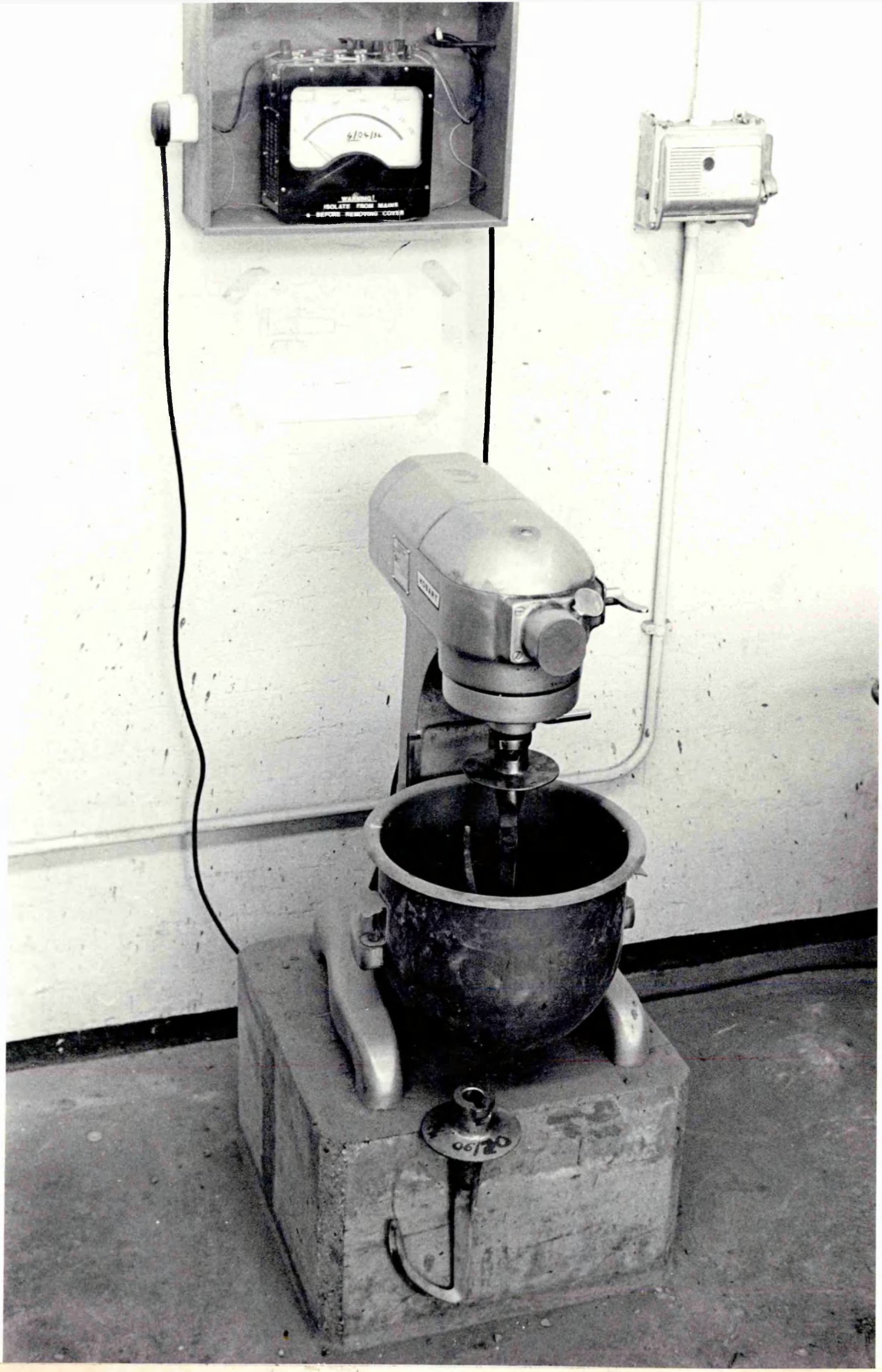


Plate 1 - 2 Point Test - Hobart A.E. 200 mixer and wattmeter (38).

6.4.9 Curing of Specimens

After manufacture, specimens (cubes, beams and cylinders) were immediately removed from the vibrating table and taken to a temperature controlled humidity room. Specimens were stored initially for a period of 24 hours at a constant temperature of 20°C ±0.1 and in a nominal relative humidity of 90%. With respect to the latter, the author took the extra precaution of covering the specimens with elastic polythene covers to maintain British Standard conditions.

After the initial curing period (24 hours) the specimens were removed from the above environment and immersed in a constant temperature (20°C ±0.1°C) water tank until the time of test.

6.5.0 Ultra-sonic Pulse Velocity determination

The ends of the specimens (prisms) were smeared with grease before immersion to prevent deterioration and consequent bad acoustic contact between the concrete and transducers. This latter also served as a couplant when subsequent tests were carried out.

6.5.1 % Weight Loss

To remove surplus scale produced by the expansive reactions of the calcium sulpho-aluminate and silicate hydrates the author used a 'standard' wire brush to apply six reciprocating horizontal strokes to each face of the cube specimen. It was then weighed to determine the weight loss.

6.5.2 Marking of Specimens

All specimens were marked, for reference purposes, with an indelible spirit pen. Specimens used in the $MgSO_4$ immersion tests were labelled by using appropriately marked elastic rubber bands so that as the specimen exfoliated the band contracted with the specimen thus retaining its identity.

6.5.3 Immersion in $MgSO_4$ (magnesium sulphate solution)

The specimens to be tested for resistance to $MgSO_4$ (100 mm cubes and 100 x 100 x 500 mm prisms) were transferred at the age of 28 days to polypropylene tanks containing a 3.5% (anhydrous) $MgSO_4$ solution.

6.5.4 Assessment of resistance to deterioration

As mentioned previously two methods were used namely:-

a) Ultra-sonic Pulse Velocity

b) % Weight Loss.

6.5.5 British Standard tests (General)

The author has deliberately omitted details of these for brevity and for information purposes has included references to the British Standards corresponding to the appropriate test in Table 6.5.7.

However, compressive and indirect tensile strength tests were carried out using an Avery-Denison T 73 compression testing machine* with appropriate platens and rigs, in accordance with BS 1881 Part 4 (32)

•

6.5.6 Cube Weights

These were recorded for each specimen tested although little emphasis has been put upon this as a form of test, except for durability where it is comparative only.

The reasons for this are listed below:-

i) Variation in specific gravities of constituent materials throughout the range

ii) The contrary effects of hydration and the above.

However, to test the hypothesis of the significance of cube weights in the assessment of performance of concrete they have been included in the correlation analysis contained in Sub-section 8.3.6.

* This machine is annually reference tested by the Cement and Concrete Association.

Table 6.5.7 Manufacture and Testing of Specimens

Age of Test (days)		1	7	14	28	91	180 (365)	Specimen Total	Specimen Weight (kg)	Total Weight (kg)	Specimen Description
Workability Tests	Slump (31)	-	-	-	-	-	-	2	15	30	-
	Compacting Factor (31)	-	-	-	-	-	-	2	15	30	-
	VeBe (31)	-	-	-	-	-	-	2	15	30	-
	2 Point Test	-	-	-	-	-	-	2	21	42	-
Strength Tests	Compressive Strength (32)	3	3	3	3	3	3	18	3	54	100mm cube
	Indirect Tensile Strength (32)	3	3	3	3	3	-	15	5	75	100mm dia x 200mm cyl.
	Flexural Strength (32)	-	-	-	2	-	-	2	15	30	100 x 100 x 500mm prism
	Ultra-sonic Pulse Vel. (33)	2	(2)	(2)	(1)	(1)		2	15	30	100 x 100 x 500mm prism
Durability Tests	% Weight loss in 3.5% $MgSO_4$				3		(3)	3	3	9	100mm cube
	% Change in U.S.P.V. in 3.5% $MgSO_4$ (33)	-	-	-	(1)	-	(1)	see above	see above	G. total= 330	100 x 100 x 500 mm prism
(i)	(ii)	(iii)	(iv)	(v)	(vi)	(vii)	(viii)	(ix)	(x)	(xi)	(xii)

Brackets denote the reuse of test specimens from previous tests.

6.5.7 Manufacture and Testing of Specimens - summary explanation of Table 6.5.7

(see column nos. at base of table)

General

This table shows a comprehensive description of the manufacturing and testing programme for the mixes. Each mix was made in two batches and testing specimens were manufactured from representative samples from each batch. Figures in brackets denote that the test was carried out using specimens from previous test.

Column details

Column (i) Type of test i.e. Workability/Strength/ Durability.

Column (ii) Name of test.

Columns (iii) - (viii) Denote the age at which specimens were tested and the number of replicates tested at that age.

Column (ix) Contains total number of all replicates used in previous tests (excluding reused specimens)

Column (x) Denotes the specimen weight allowance in accordance with BS 1881, Part 3. (46)

Column (xi) Contains the aggregate weight of concrete needed for each test i.e. column (ix) multiplied by column (x).

This figure is not entered if specimens were used from a previous test. Included at the bottom of column (xi) is the grand total of concrete required for each mix (i.e. 2 batches).

Column (xii) Contains the specimen description including dimensions and shape.

7.0 Analysis of Results

7.1 Introduction

In this Chapter the author will describe the analytical methods used on the experimental data including the computer aids used in this respect.

7.2 Analytical Methods

The methods used to analyse the experimental data needed to comply with three primary objectives as follows:-

i) The establishment of correlations between testing methods.

ii) The assessment of the effects of mix constituents upon the properties of concrete.

iii) An assessment of the effects of age upon the above.

The testing methods have previously been described and the author does not wish to pursue this in further detail. However, during the course of the testing programme it was found that, certain testing methods were more consistently sensitive to changes in the concrete properties. It was therefore decided after the plotting of some preliminary data that to avoid duplication, representative tests should be chosen for each of the properties being measured to act as sensors for the mix variables being investigated. To assist with this and additionally to provide further information regarding the interrelationships between the testing methods correlation analysis was performed upon the workability and strength test data. To supplement this, single variable analyses were carried out on each workability and strength test for the control mixes at each age (where applicable) to assess the variability of each test method.

Results showed the following tests to be the least variable and generally the most sensitive for determining the appropriate properties listed below:-

Test	Property
Compacting Factor	Workability
Compressive Strength	Strength
% weight loss	Durability

The durability tests were not scrutinised by the application of comparative single variable analysis or correlation analysis but comparative observation of results showed the Ultra-sonic Pulse velocity method to be much less sensitive to visual changes observed than the % weight loss technique.

The three representative tests having been selected, the author considered that the properties of the different mixes should be related to those of the control by comparing the properties derived using these tests. This has been described previously (Chapter 4). However, it must be emphasised at this stage, that although the control limits superimposed upon the graphs contained in the next section are in accordance with clause 6.8.2 CP 110, no attempt was made to implement the compliance criteria upon the data collected as to do so would have been disproportionately time and effort consuming. It must be added further that the strength test control limits refer only to 28 day control strengths. This is to simplify result interpretation in the context of the desired objectives.

On this basis any test result falling outside these control limits was considered to have departed significantly from that of the control.

The third objective outlined in this section, that of assessing the effect of age upon mix properties was more difficult. The measurement of pozzolanic activity has been referred to previously and previous assessments have measured this in a relative sense.

The author considered that if considerable pozzolanic activity had taken place throughout the testing programme it could be detected by comparing the correlation between mix properties and proportions and types of mix constituents at different ages. The mix properties chosen were as follows:-

Mix properties	Mix constituents
Compressive Strength	Cement
Indirect Tensile Strength	Pozz. 1 or 2
Ultra-sonic Pulse velocity	Fine aggregate
Cube weight	

The correlation between properties and constituents was determined at 7, 28 and 91 days. The hypothesis was that any pozzolanic activity developing at later ages would manifest itself by a positive change in correlation coefficient between pozzolana content and the physical properties of the concrete. Results are contained in Chapter 8 and these will be discussed in Chapter 9.

The author now proposes to elaborate on the analytical methods used and the assumptions made.

7.2.1 Single variable analysis (59, 60)

For calculation of the mean, standard deviation and coefficient of variation of the control population the author made the following assumptions in accordance with common practice.

i) That the following parameters were based on an infinite normal population.

ii) That the population mean $\bar{X}$ is as follows:

$$\bar{X} = \frac{1}{N} \sum_{i=1}^{m} Xi$$

where N = number of results

and Xi = value of the i^{th} result.

iii) That the population standard deviation (s) is as follows:

$$s = \sqrt{\frac{1}{(N - 1)} \cdot \sum_{i = 1}^{m} (Xi - \bar{X})^2}$$

where this is the best estimate from a sample size 'N'.

The coefficient of variation (U) is as follows:

$$U = \frac{s}{\bar{X}} \times 100$$

7.2.2 Regression and Correlation analysis (59, 60)

For relationships between tests the author has included regression equations together with the corresponding correlation coefficients (see Chapter 8).

For the relationships between mix properties and constituents the regression equations are omitted and correlation coefficients only are included. (see Chapter 8)

The regression lines to which data has been fitted are linear or log linear as follows:-

(1) $Y = A + BX.$

(2) $\ln Y = \ln A + BX$ i.e. $Y = Ae^{BX}$

(3) $\ln Y = \ln A + B \ln X$ i.e. $Y = Ax^{B}$

Data is fitted to the above curves on the basis of the least squares criterion such that for normal regression lines constants A and B are as follows:-

$$A = \frac{\Sigma X \quad \Sigma XY \quad - \quad \Sigma Y \quad \Sigma X^2}{(\Sigma X^2) \quad - \quad N \; (\Sigma X^2)}$$

$$B = \frac{XY \quad - \quad \frac{(\Sigma X)\;(\Sigma Y)}{N}}{X^2 \quad - \quad \frac{(\Sigma X)^2}{N}}$$

where X = independent variable.

Y = observed value associated with appropriate value of X (dependent variable).

$$\text{Hence} \quad R = \frac{N\Sigma XY \quad - \quad \Sigma X\Sigma Y}{\sqrt{\left[N\Sigma X^2 - (\Sigma X)^2\right]\left[N\Sigma Y^2 \quad - \quad (\Sigma Y)^2\right]}}$$

where R = coefficient of correlation between variables X and Y.

7.2.3 Computer Aids

Correlation analysis on mix parameters was obtained using an IBM standard program 'STATPK' (see T. 8.3.6.1 - T. 8.3.6.6). Regression analysis was achieved using an amended version of another IBM standard program 'CURFIT'. All work was done on an IBM 370.

CHAPTER 8

RESULTS FROM TESTING PROGRAMME

8.0 RESULTS FROM TESTING PROGRAMME

8.1 Introduction

This chapter contains a graphical account of the principal findings of the author. These include relationships between mix parameters workability and strength together with the interrelationships between the various testing techniques. Also included in this chapter are tables of correlation relating mix parameters to those of hardened concrete properties.

In the majority of cases, points have been included on the graphs representing numerical values which can be found in Appendices I - V. Where points have been omitted, values have been interpolated from existing data unless otherwise stated by the author in Chapter 9.0.

A further feature of this chapter is the inclusion of the mean Control (00/00/50) and 90% confidence limits for workability and strength. These have been included to facilitate comparison between different graphs.

Although interrelationships between different testing methods are dealt with, Compacting Factor (Workability) and Compressive Strength (Strength) have been chosen as the comparators for assessing quality.

The data from which the graphs are compiled is included at the back of the text (with the exception of 1 day and 182 day tests) in Appendices I - V.

SYMBOLS

For graphs:-

G. 8.2.11. - 3

- - - - -		90% Upper confidence limit (Control)
—— - ——	denotes	Mean Compacting Factor (Control)
- - - - -		90% Lower confidence limit (Control)

For graphs:-

G. 8.3.1.1. - 4

- - - - -		90% Upper confidence limit (Control)
————	denotes	Mean control (00/00/50) value.
- - - - -		90% Lower confidence limit (Control)

For graphs:-

G. 8.3.2.1. - 3

G. 8.3.3.1. - 9

- - - - -		90% Upper confidence limit (Control)
—— - ——	denotes	Mean 28 day Compressive Strength (Control)
- - - - -		90% Lower confidence limit (Control)

N.B. 90% confidence limits placed at $\pm$ 1.64 standard deviations (s) from the Mean ($\bar{x}$).

'% Cement replacement'	<u>denotes</u>	replacement of given percentage of Ordinary Portland Cement (<u>weight or volume</u>) with an equal <u>volume</u> of Pozzolan 1 <u>OR</u> Pozzolan 2.
'% Fine aggregate replacement'	<u>denotes</u>	replacement of given percentage of fine aggregate (<u>weight or volume</u>) with an equal <u>volume</u> of Pozzolan 1 <u>OR</u> Pozzolan 2.

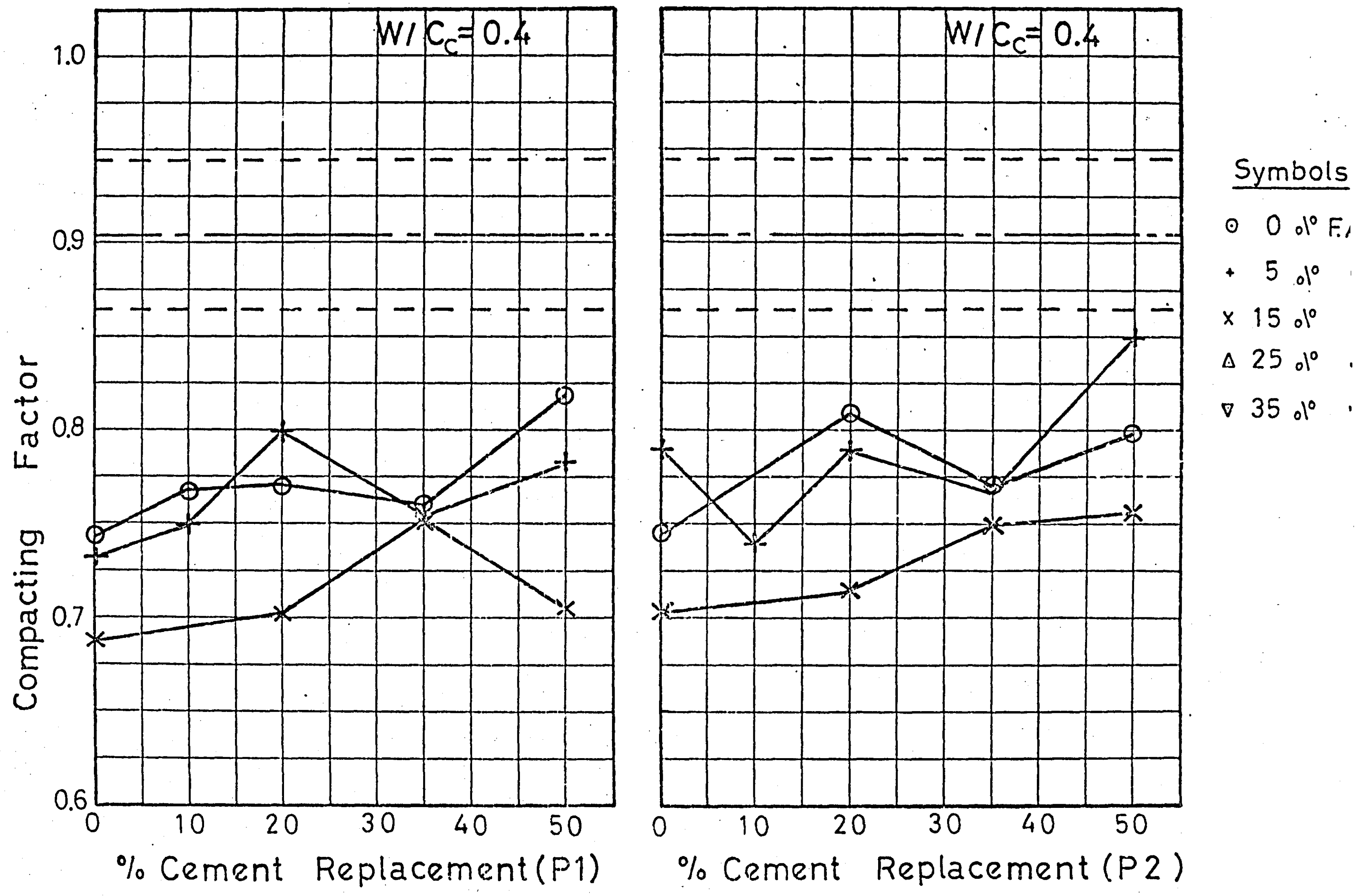
8.2 <u>Workability Tests</u>

comprising graphs and tables:-

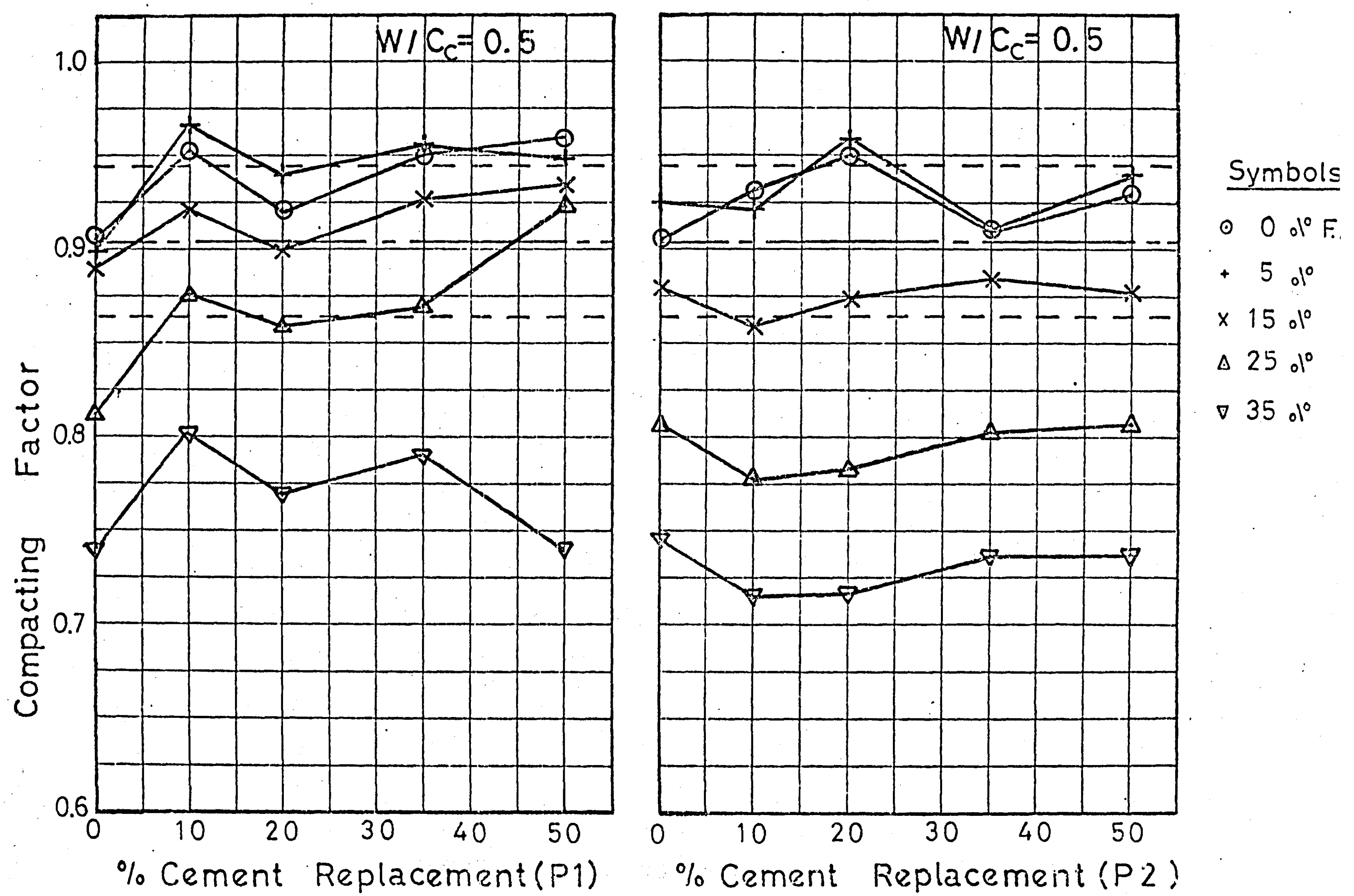
G. 8.2.1.1 - 3.

G. 8.2.2.1/2

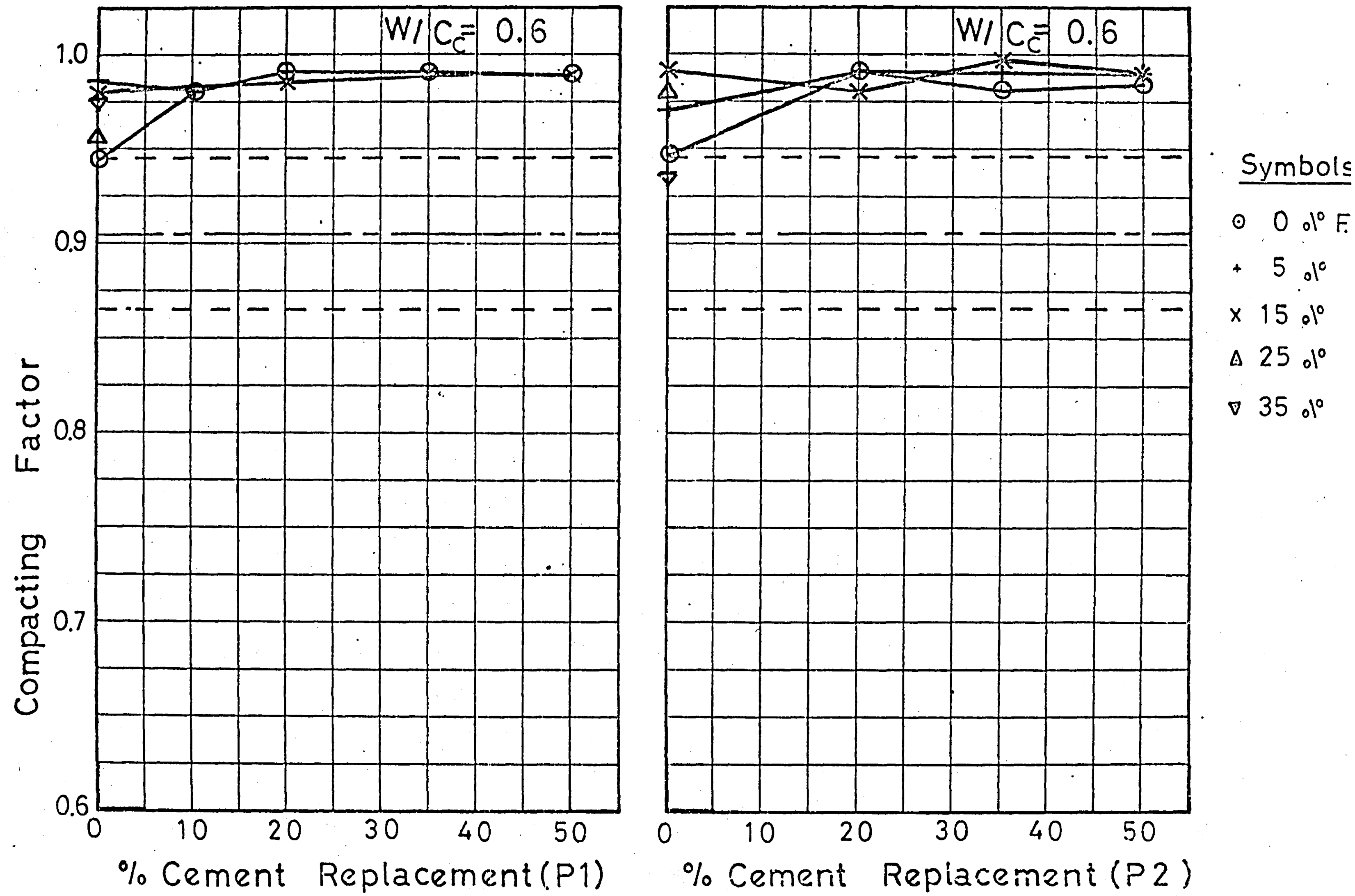
T. 8.2.3



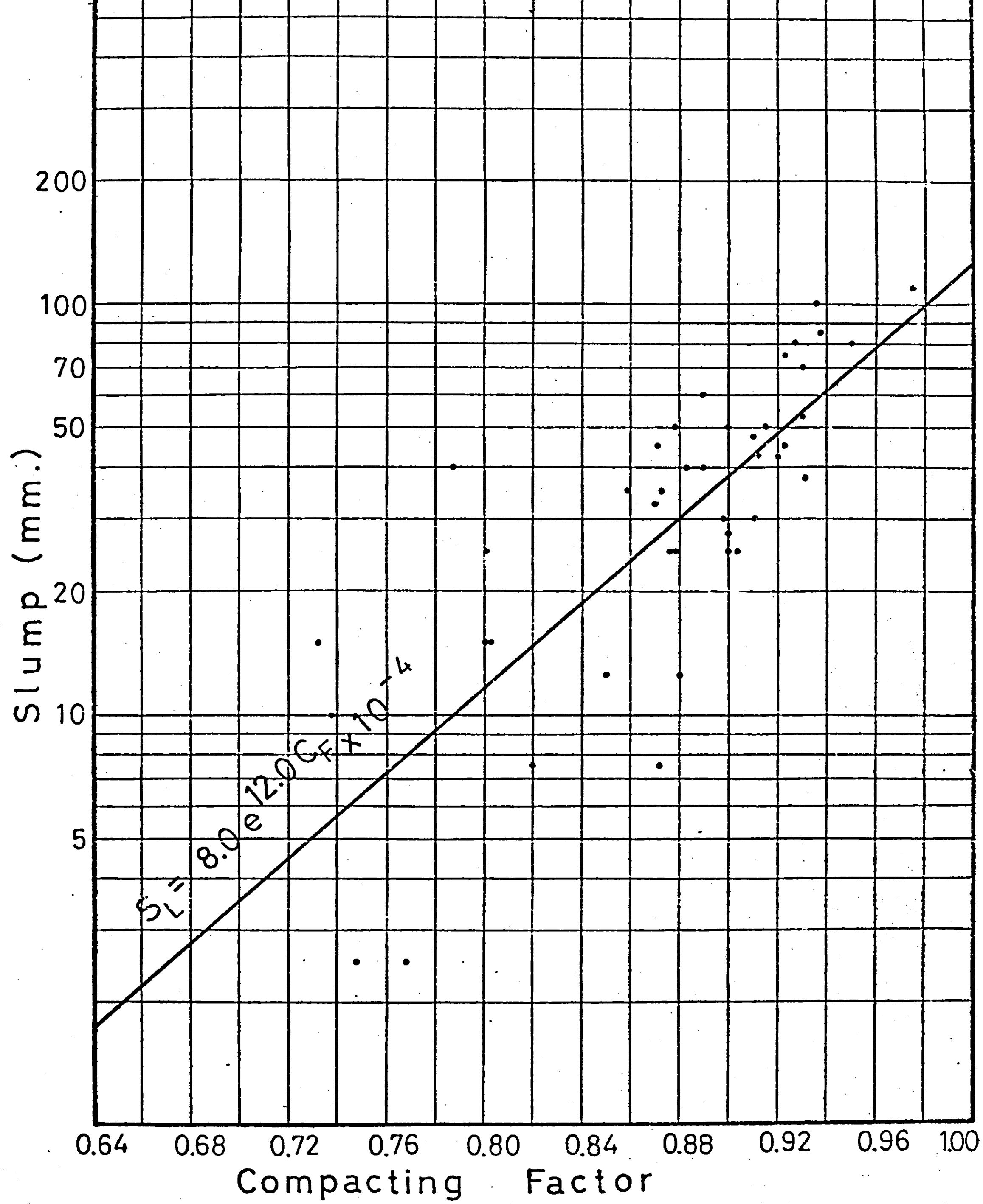
G. 8.2.1.1 Compacting Factor v. % Cement Replacement



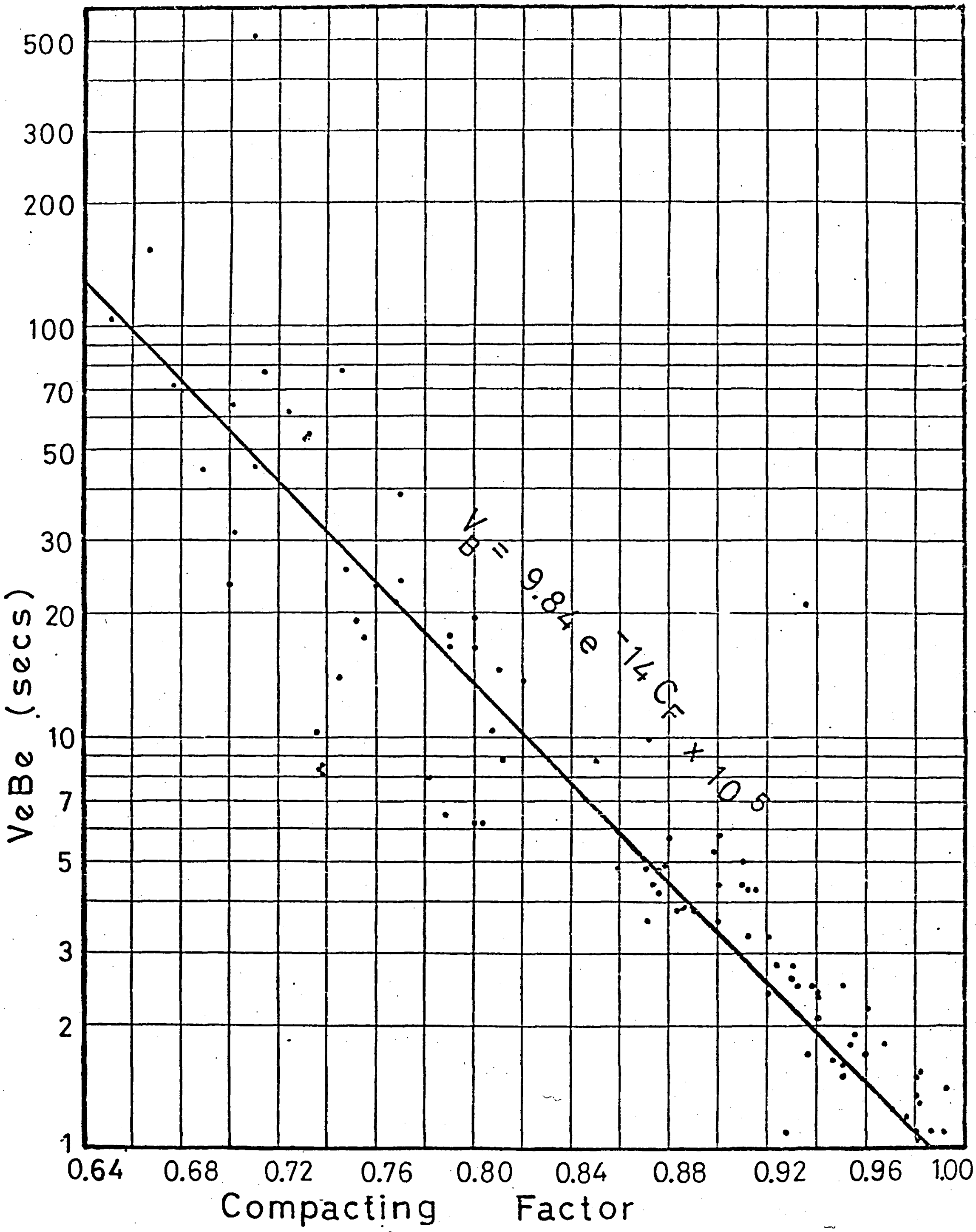
G.8.2.1.2 Compacting Factor v. % Cement Replacement



G.8.21.3 Compacting Factor v. % Cement Replacement



G. 8.2.2.1 Slump v Compacting Factor



G.8.222 VeBe v. Compacting Factor

CORRELATION COEFFICIENTS

WORKABILITY TESTS

	SLUMP	VeBe	COMPACTING FACTOR	2 POINT TEST (YIELD)	2 POINT TEST (SLOPE)
SLUMP	1.00	-0.88	0.81	-0.40	-0.32
VeBe	-0.88	1.00	-0.93	-0.23	0.29
COMPACTING FACTOR	0.81	-0.93	1.00	-0.69	-0.69
2 POINT TEST (YIELD)	-0.40	0.23	-0.69	1.00	0.52
2 POINT TEST (SLOPE)	-0.32	0.29	-0.69	0.52	1.00

8.3 Strength Tests

comprising graphs and tables:-

G. 8.3.1.1 - 5.

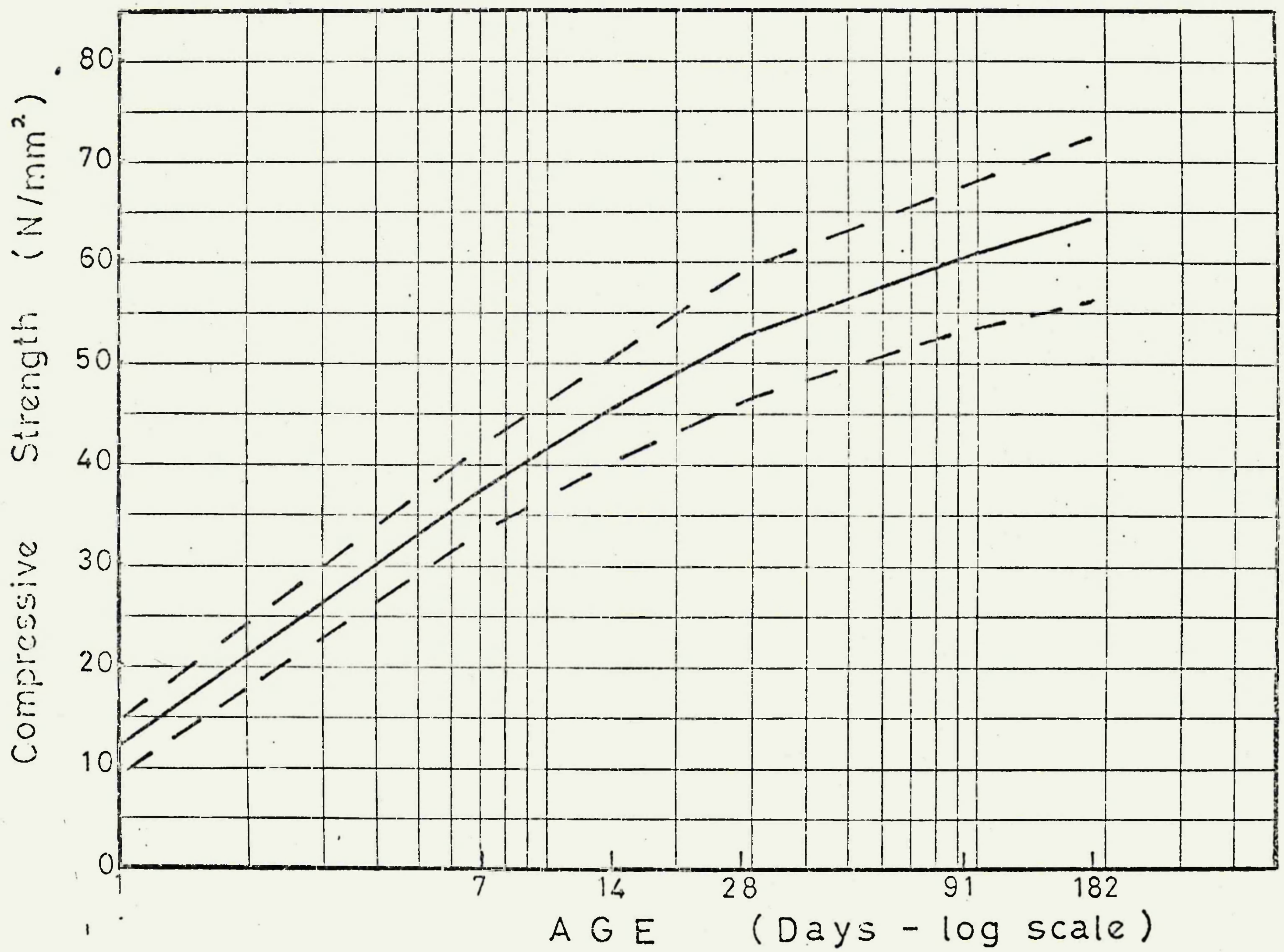
G. 8.3.2.1 - 3.

G. 8.3.3.1 - 9.

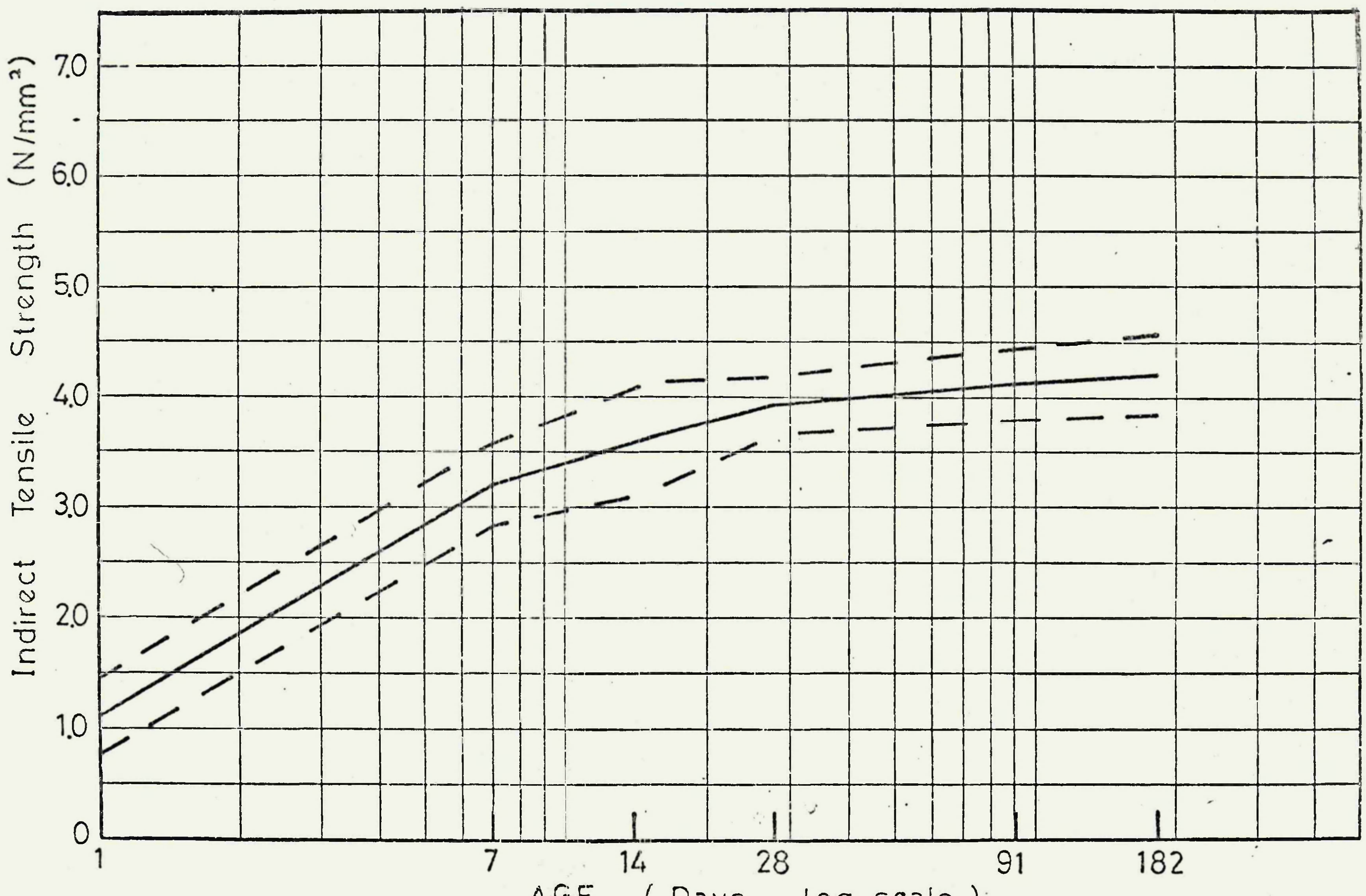
G. 8.3.4

G. 8.3.5.1 - 4.

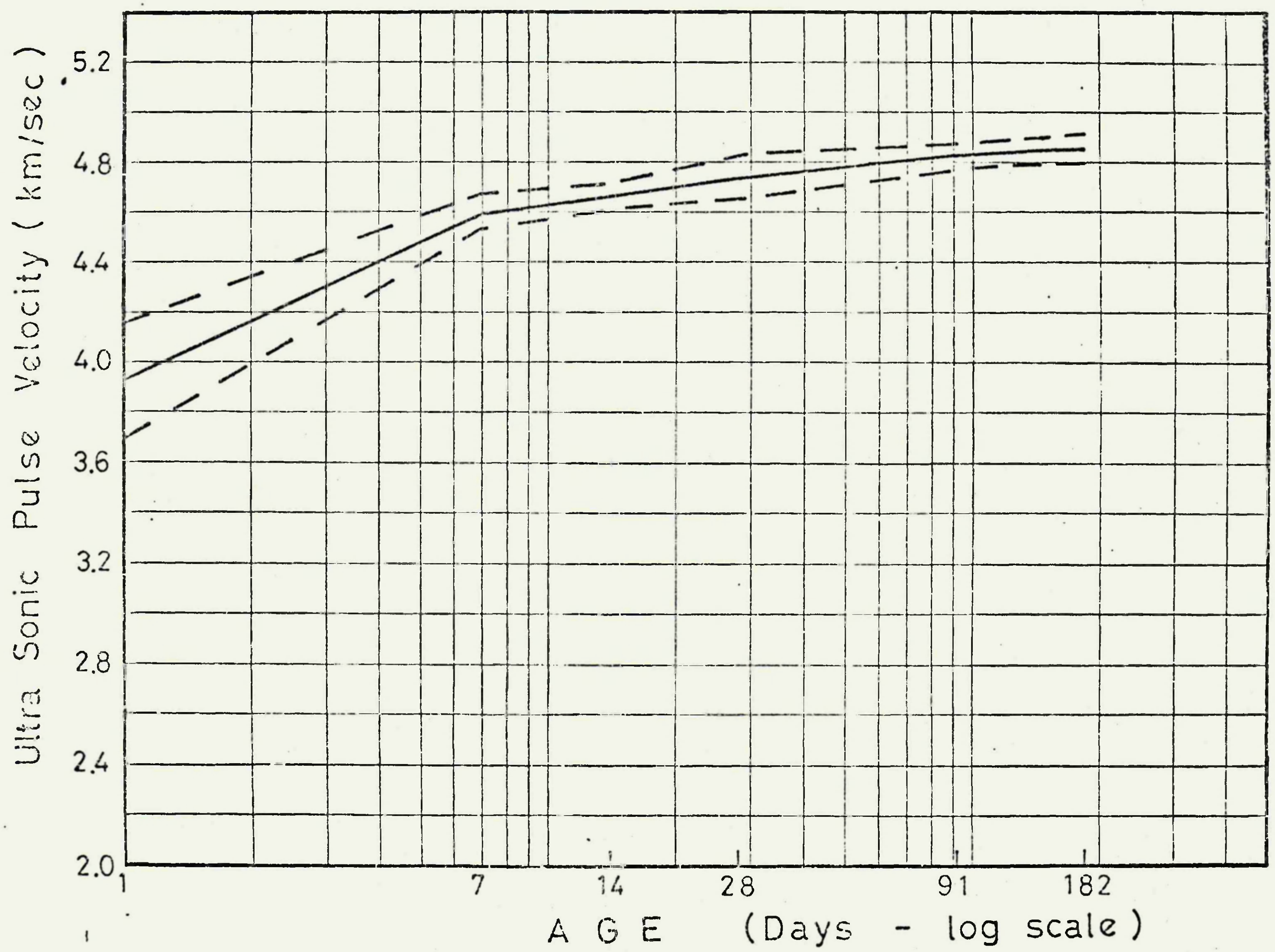
T. 8.3.6.1 - 6.



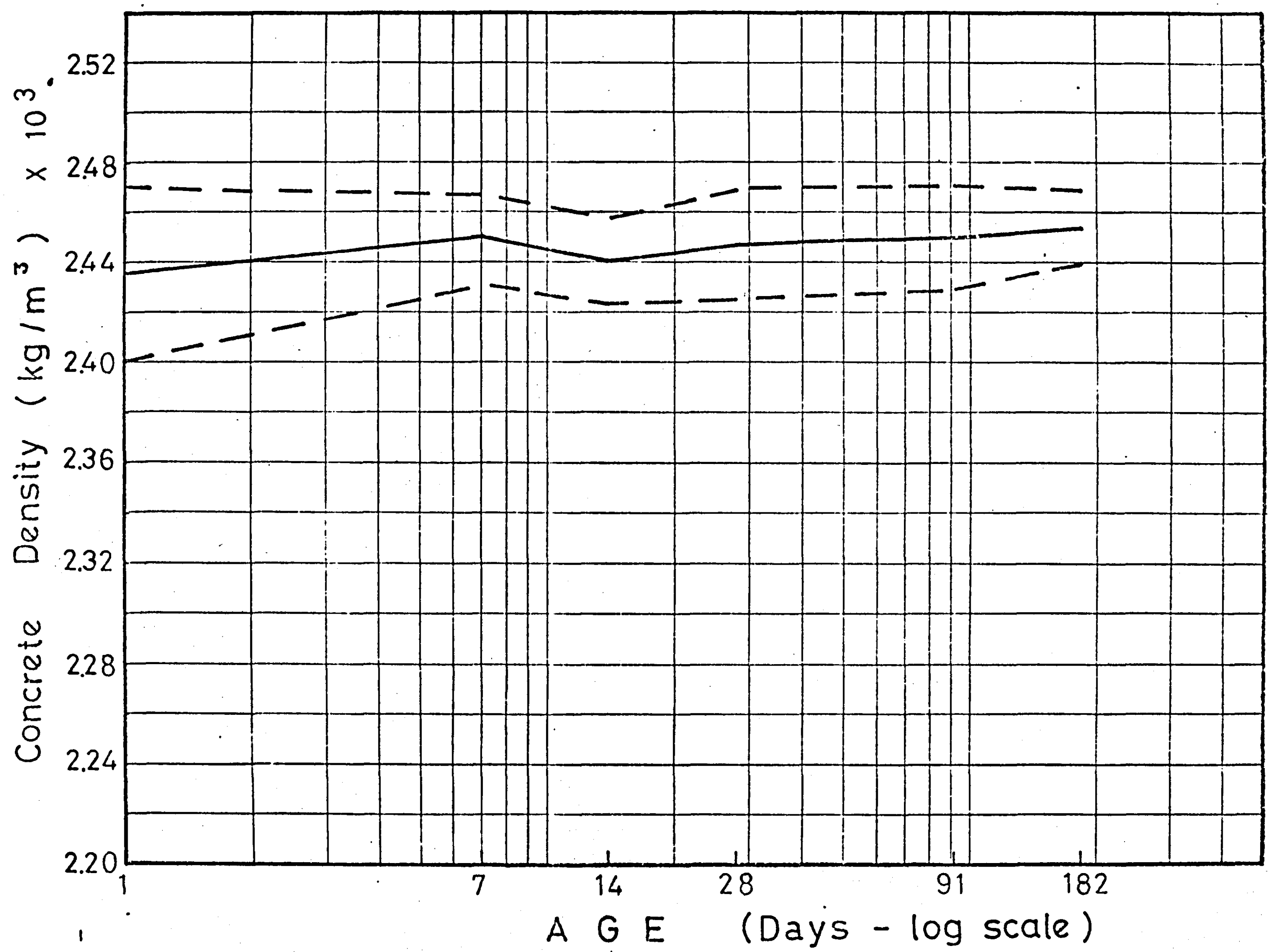
G.8.3.1.1 Compressive Strength v. Age - Control



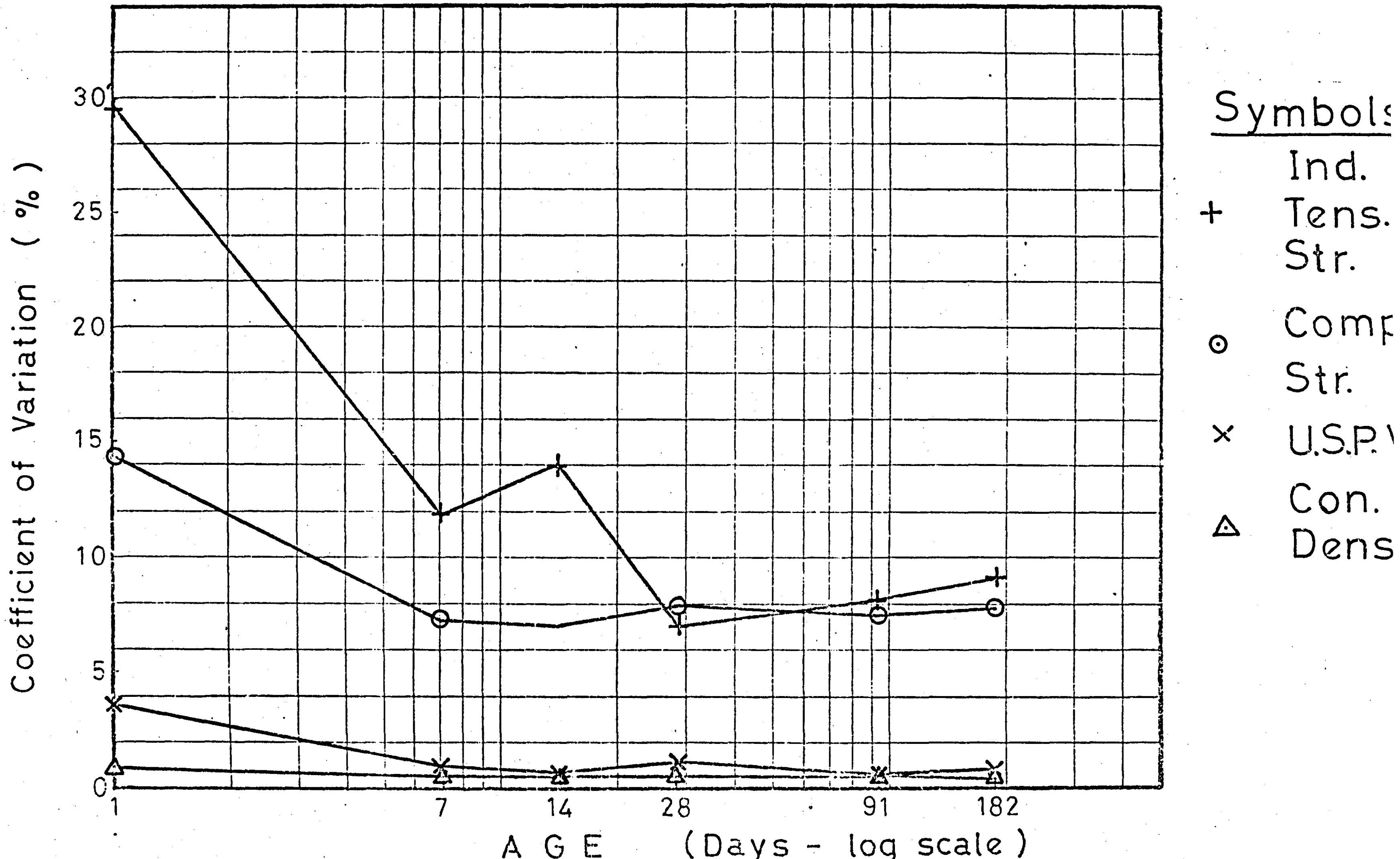
G.8.3.1.2 INDIRECT TENSILE STRENGTH v. AGE - CONTROL



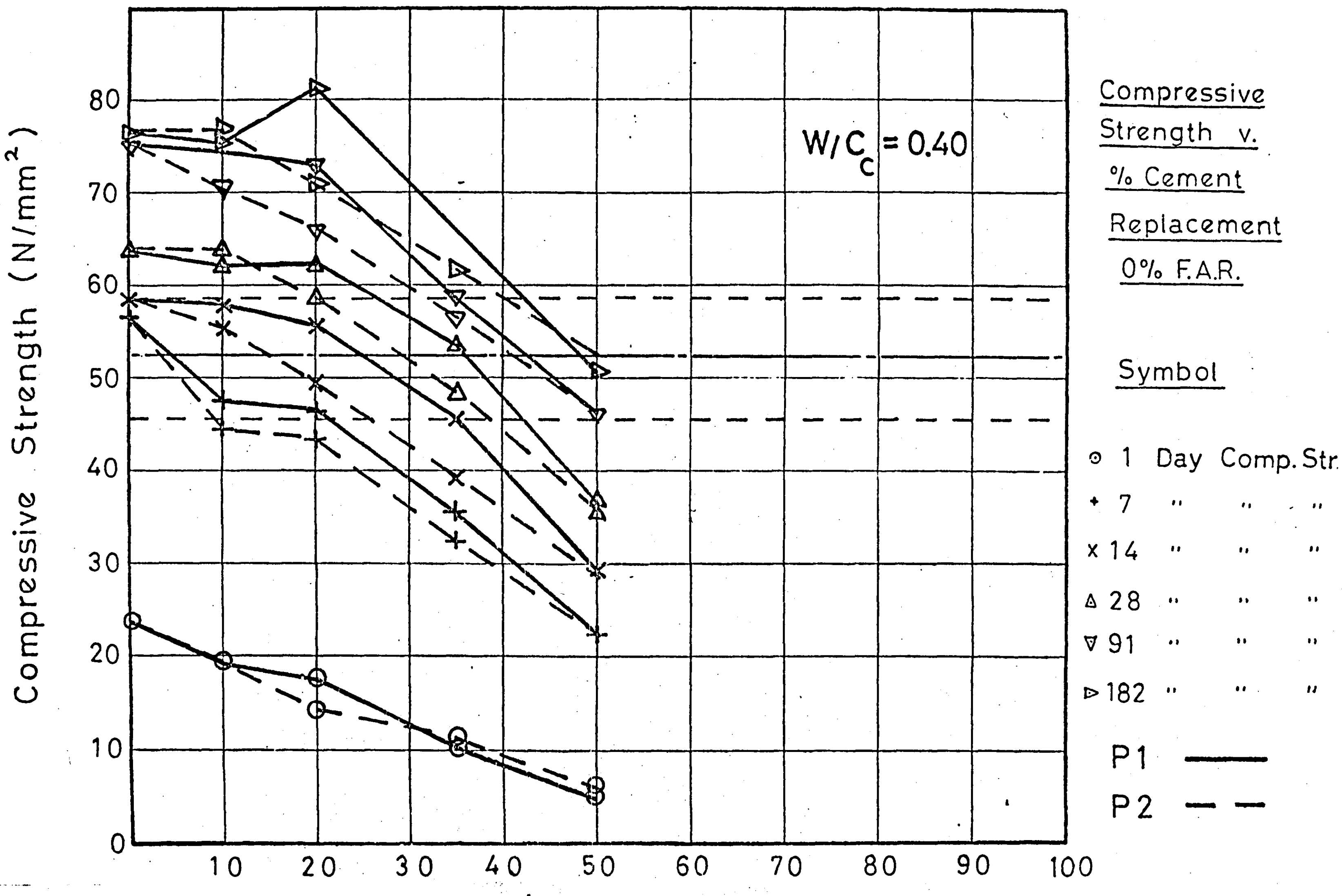
G.8.3.1.3 Ultra Sonic Pulse Velocity v. Age - Control



G.8.3.14 Concrete Density v. Age - Control

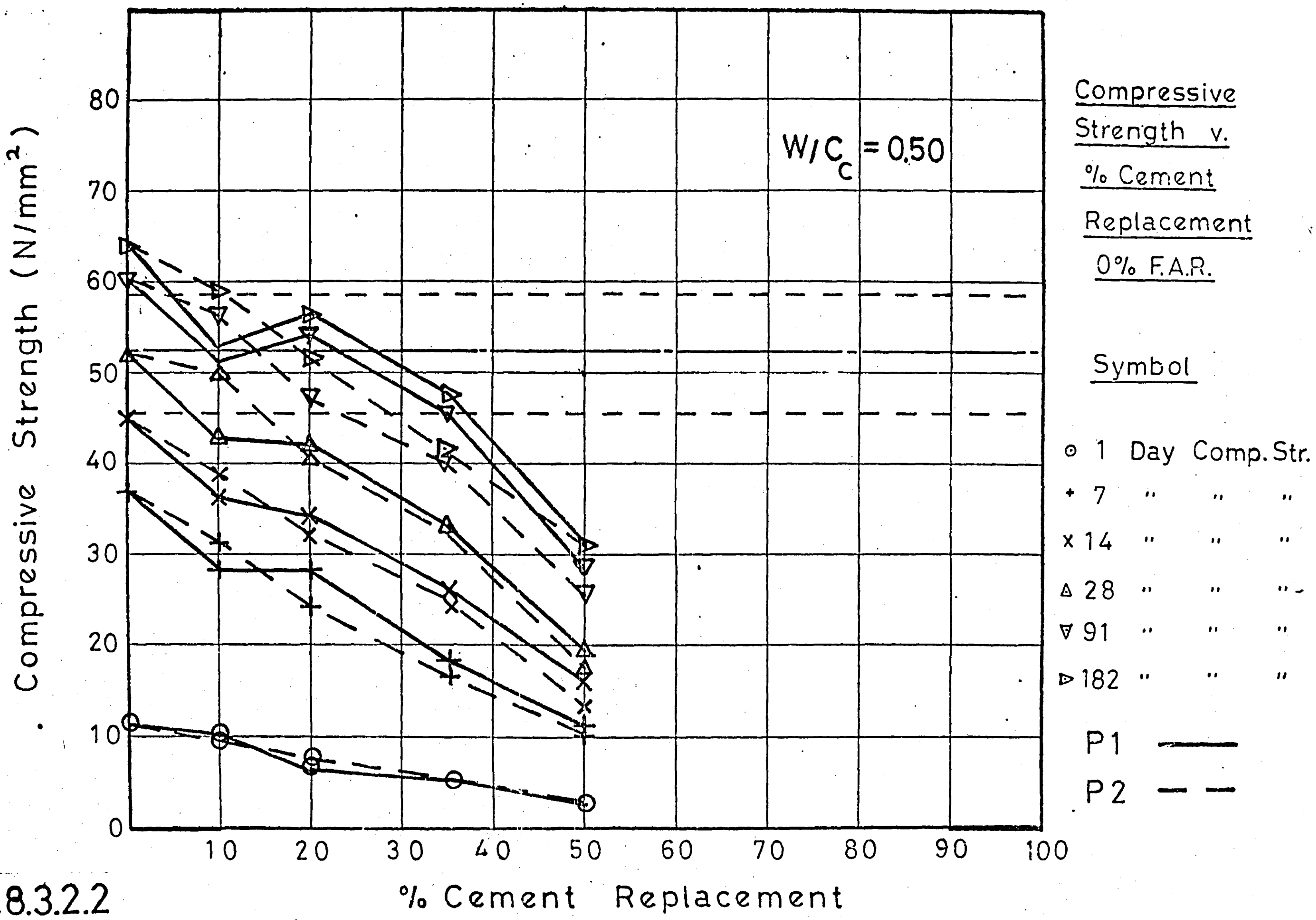


G.8.3.1.5 Coefficient of Variation v. Age - Control



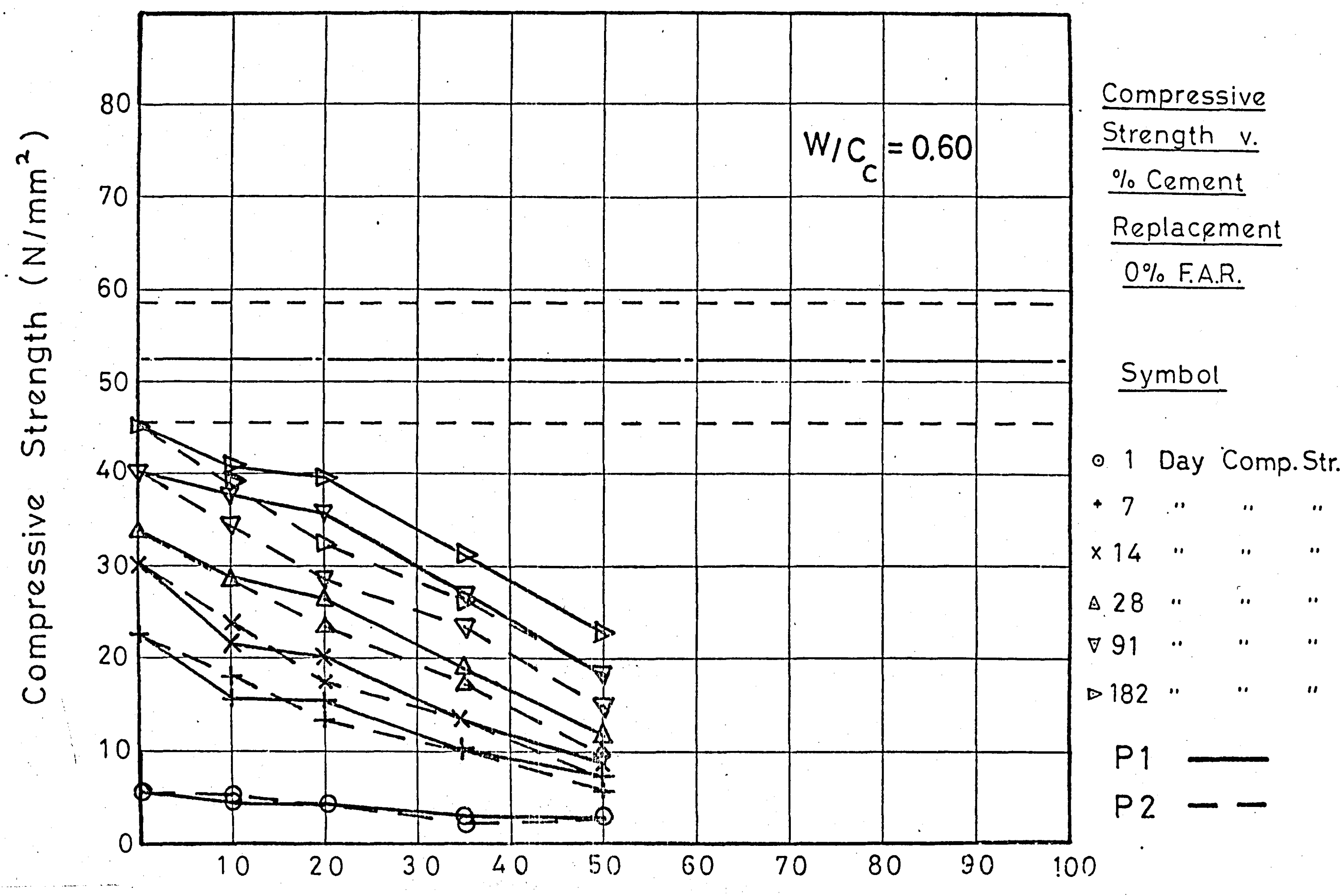
Compressive Strength (N/mm²)
0
10
20
30
40
50
60
70
80
10
20
30
40
50
60
70
80
90
100
% Cement Replacement
W/Cc = 0.40
Compressive Strength v. % Cement Replacement
0% F.A.R.
Symbol
⊙ 1 Day Comp. Str.
+ 7 " " "
x 14 " " "
△ 28 " " "
▽ 91 " " "
▷ 182 " " "
P1
P2

G.8.3.2.1



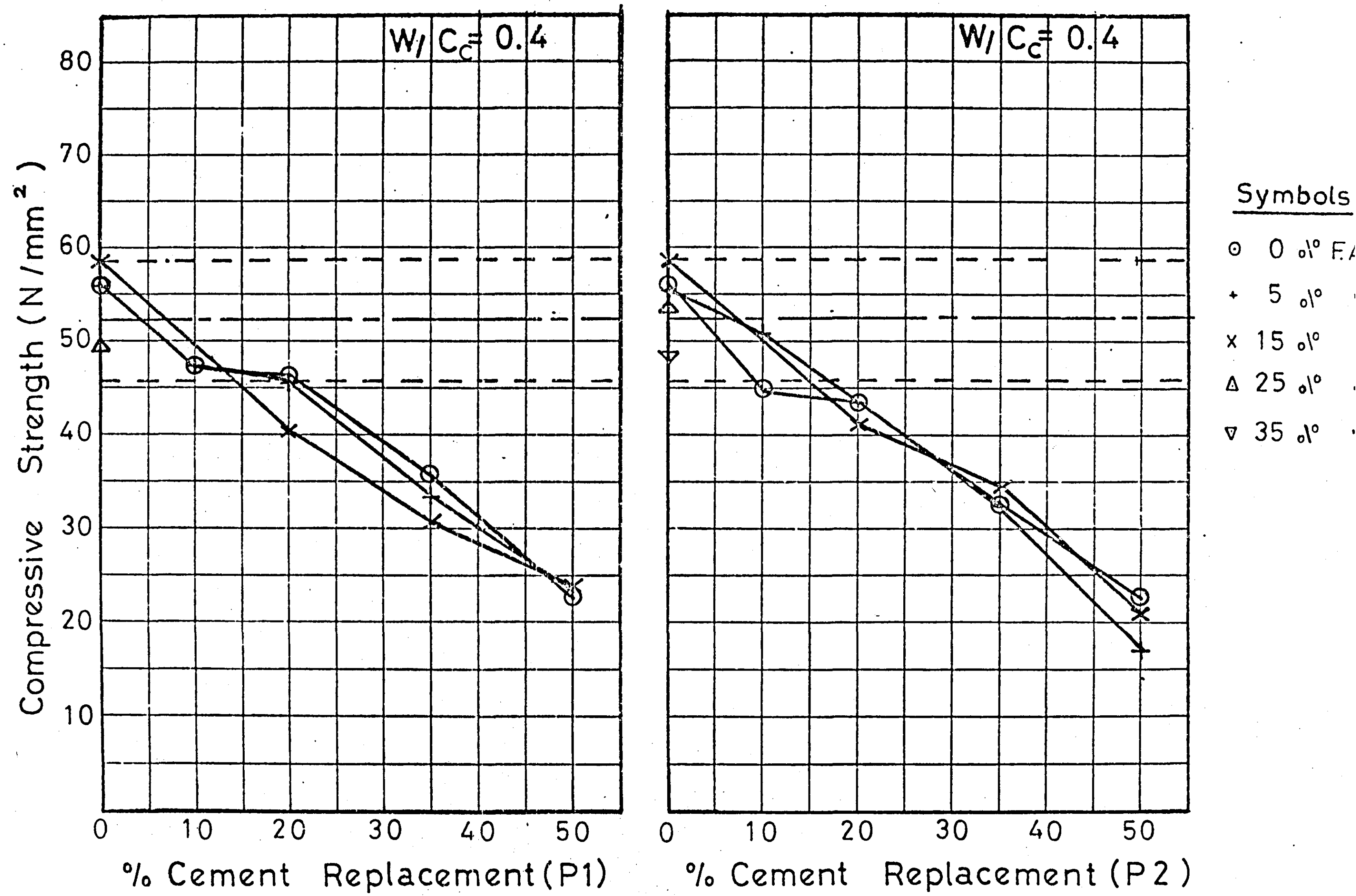
Compressive Strength (N/mm²)
0
10
20
30
40
50
60
70
80
W/C$_c$ = 0.50
10
20
30
40
50
60
70
80
90
100
% Cement Replacement
Compressive Strength v. % Cement Replacement
0% F.A.R.
Symbol
⊙ 1 Day Comp. Str.
+ 7 " " "
× 14 " " "
△ 28 " " "
▽ 91 " " "
▷ 182 " " "
P1
P2

G.8.3.2.2

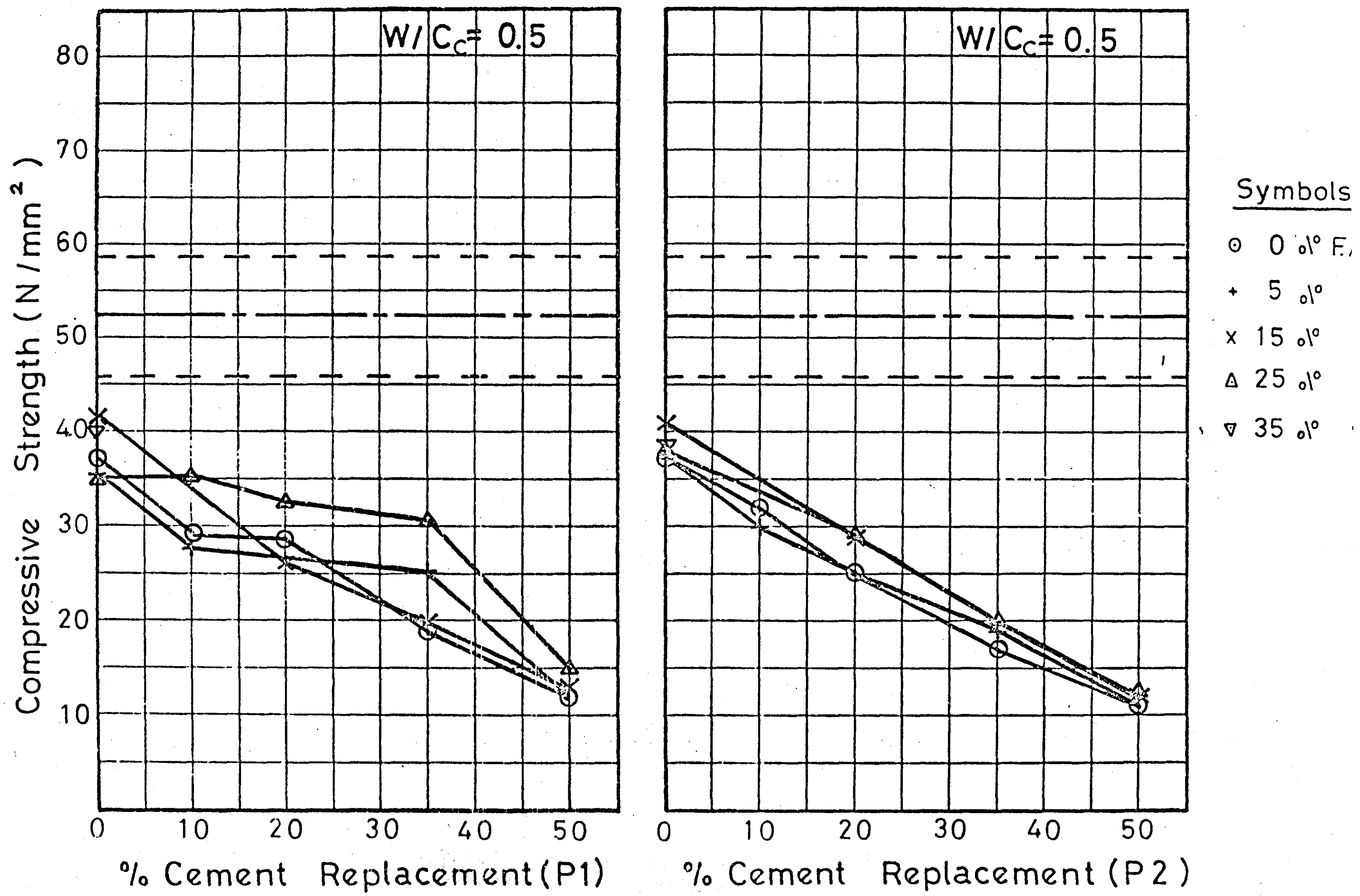


W/Cc = 0.60
Compressive Strength (N/mm²)
0
10
20
30
40
50
60
70
80
10
20
30
40
50
60
70
80
90
100
% Cement Replacement
Compressive Strength v. % Cement Replacement 0% F.A.R.
Symbol
⊙ 1 Day Comp. Str.
+ 7 " " "
× 14 " " "
△ 28 " " "
▽ 91 " " "
▷ 182 " " "
P1
P2

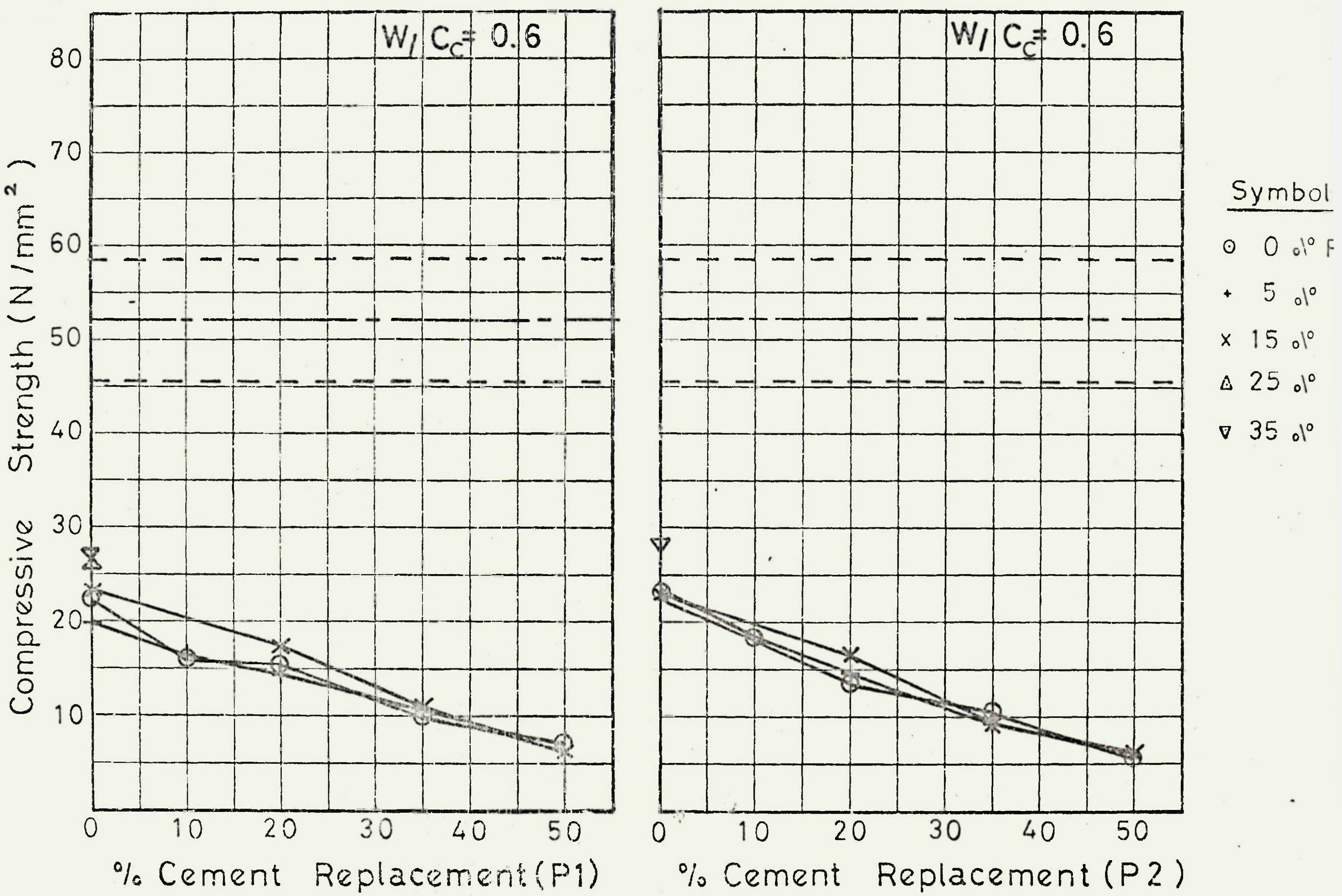
G.8.3.2.3



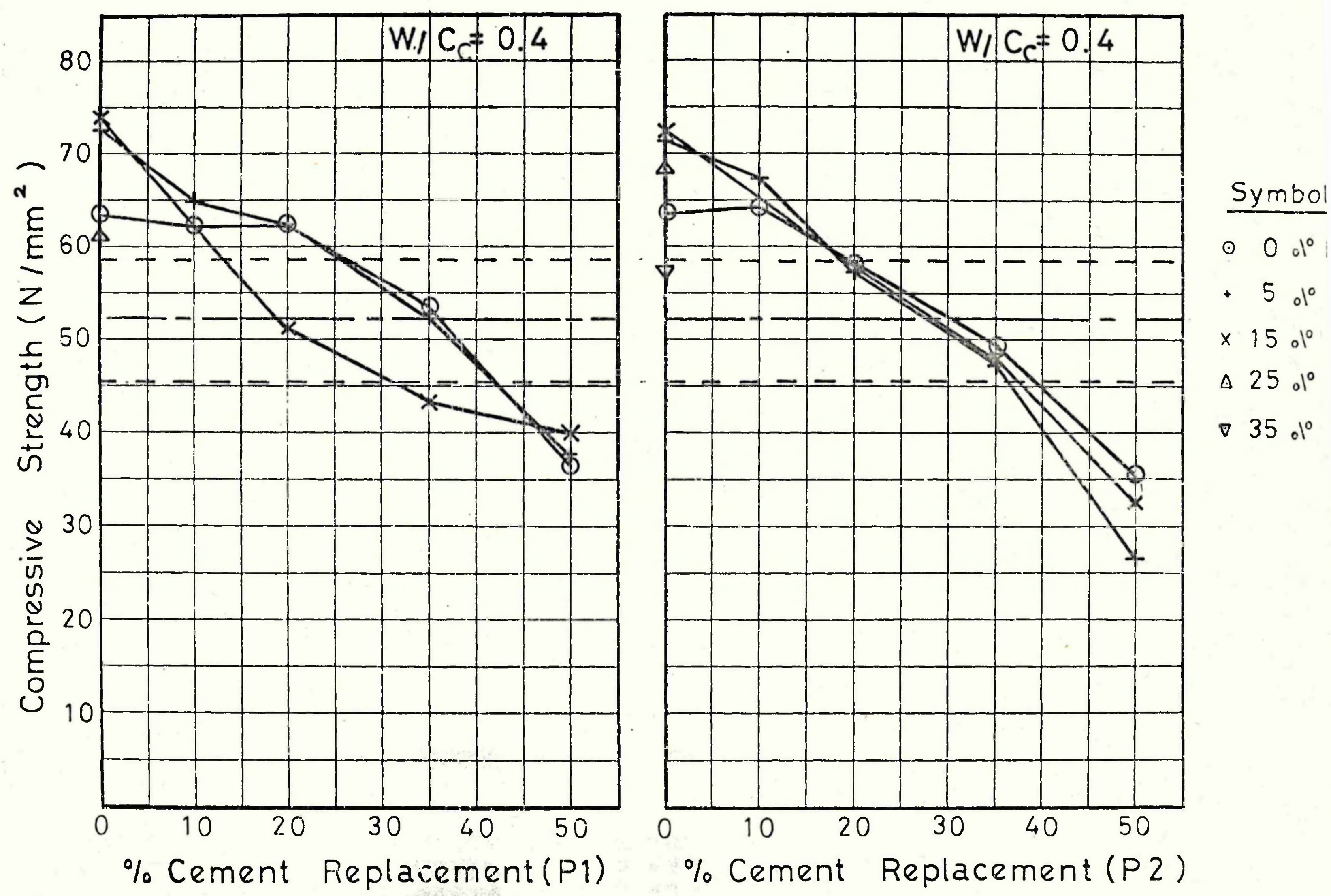
G. 8.3.3.1 7 Day Compressive Strength v. % Cement Replacement



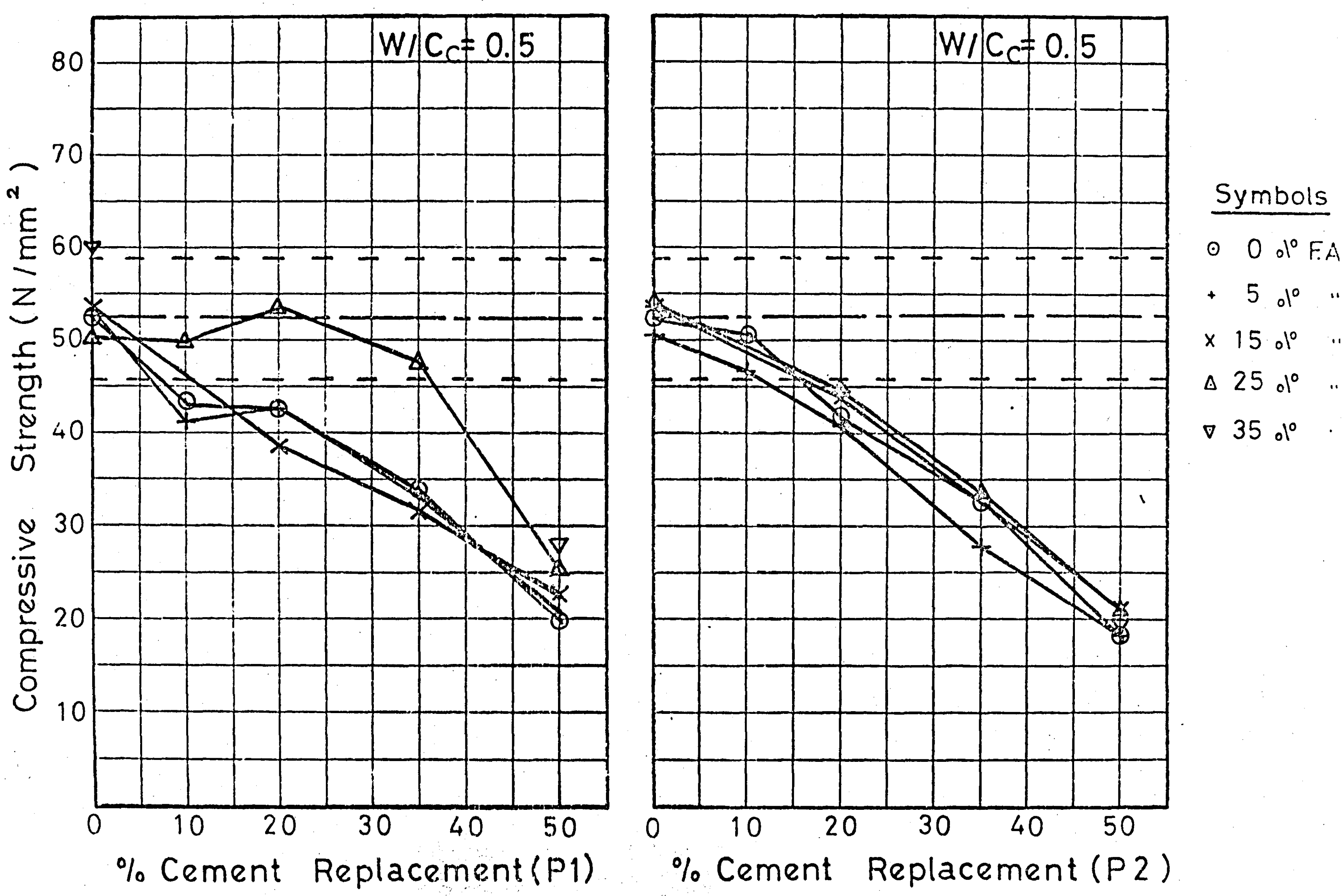
G.8.3.3.2 7 Day Compressive Strength v. % Cement Replacement



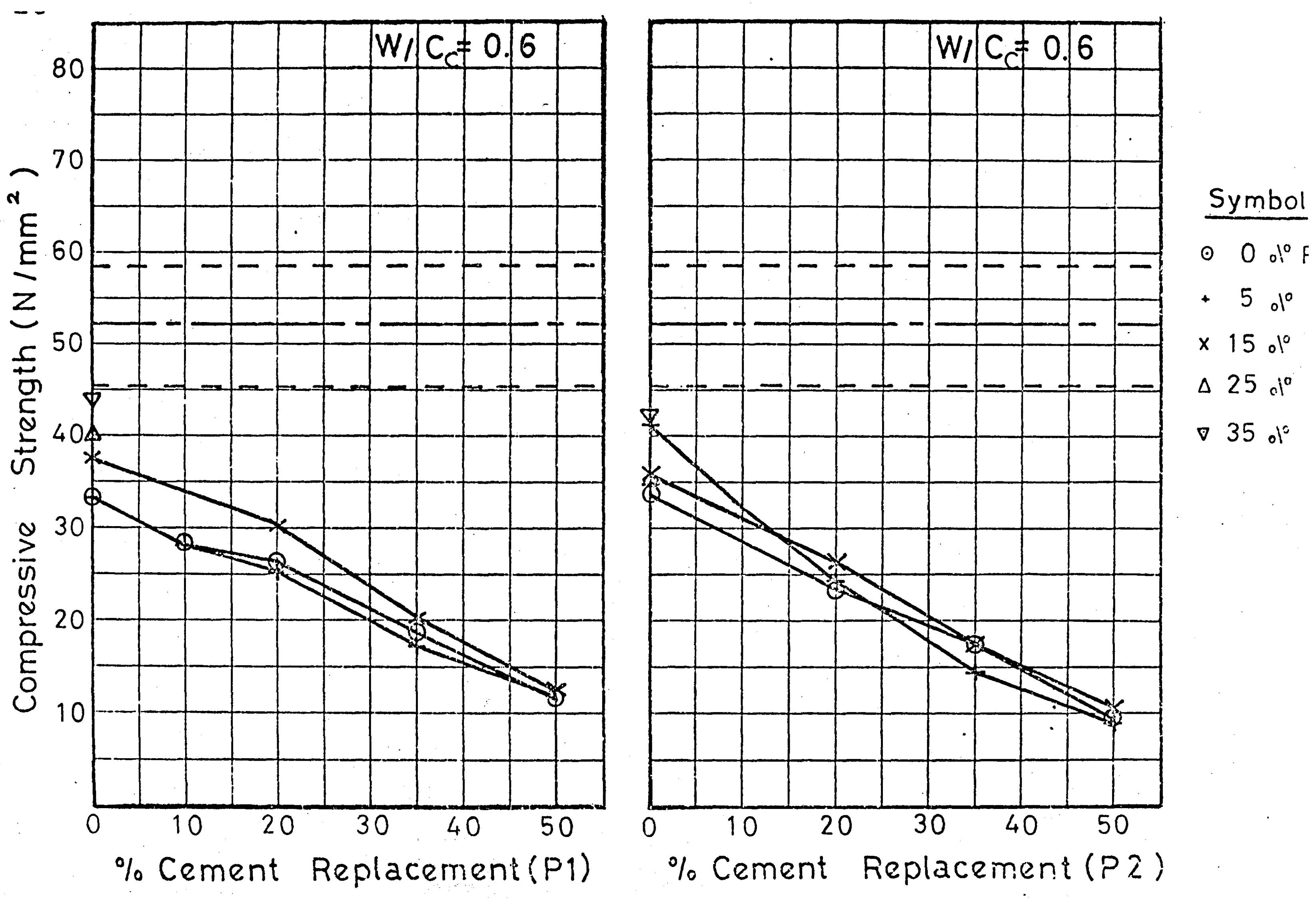
G.8.3.3.3 7 Day Compressive Strength v. % Cement Replacement



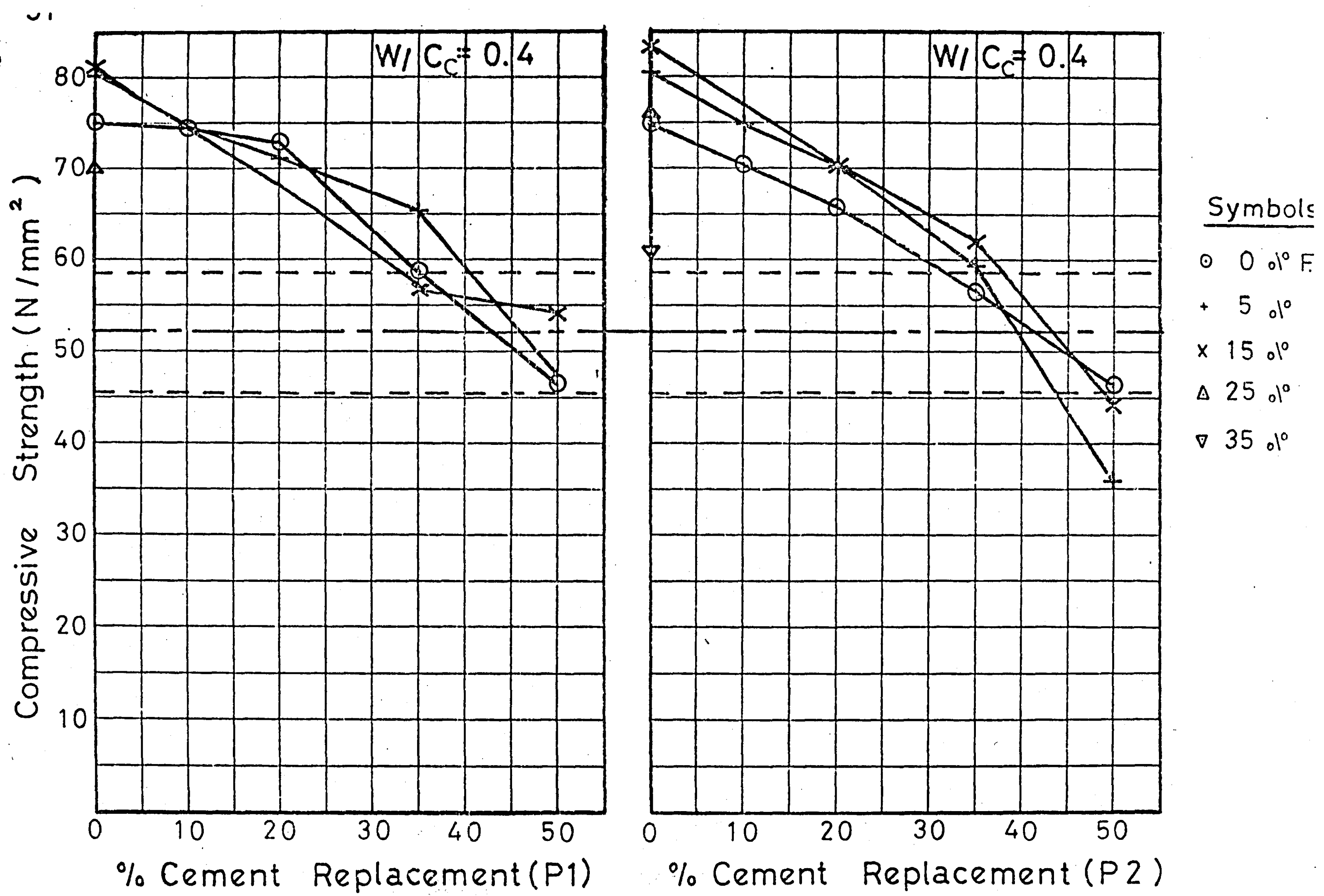
G.8.3.3.4 28 Day Compressive Strength v. % Cement Replacement



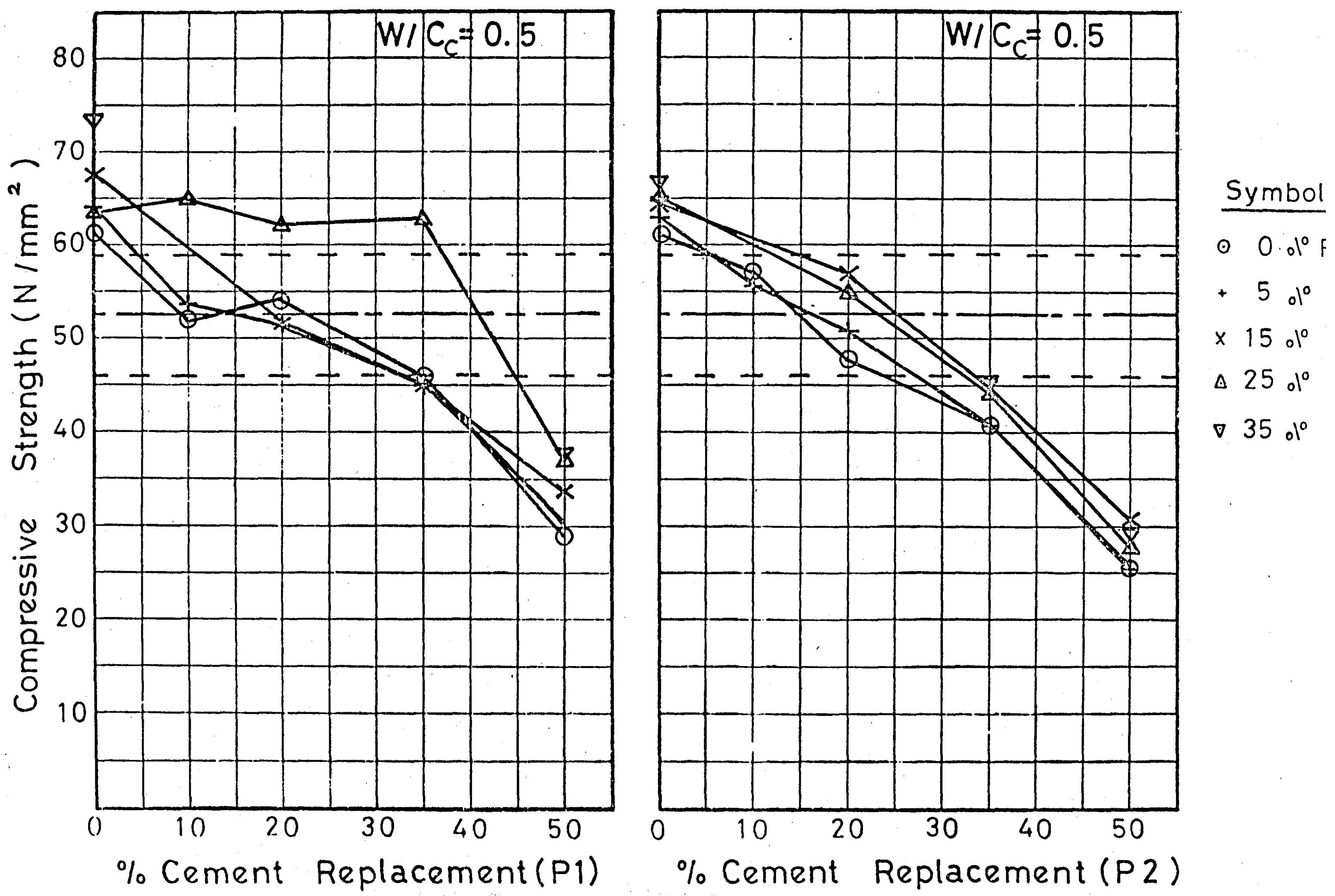
G.8.3.3.5 28 Day Compressive Strength v. % Cement Replacement



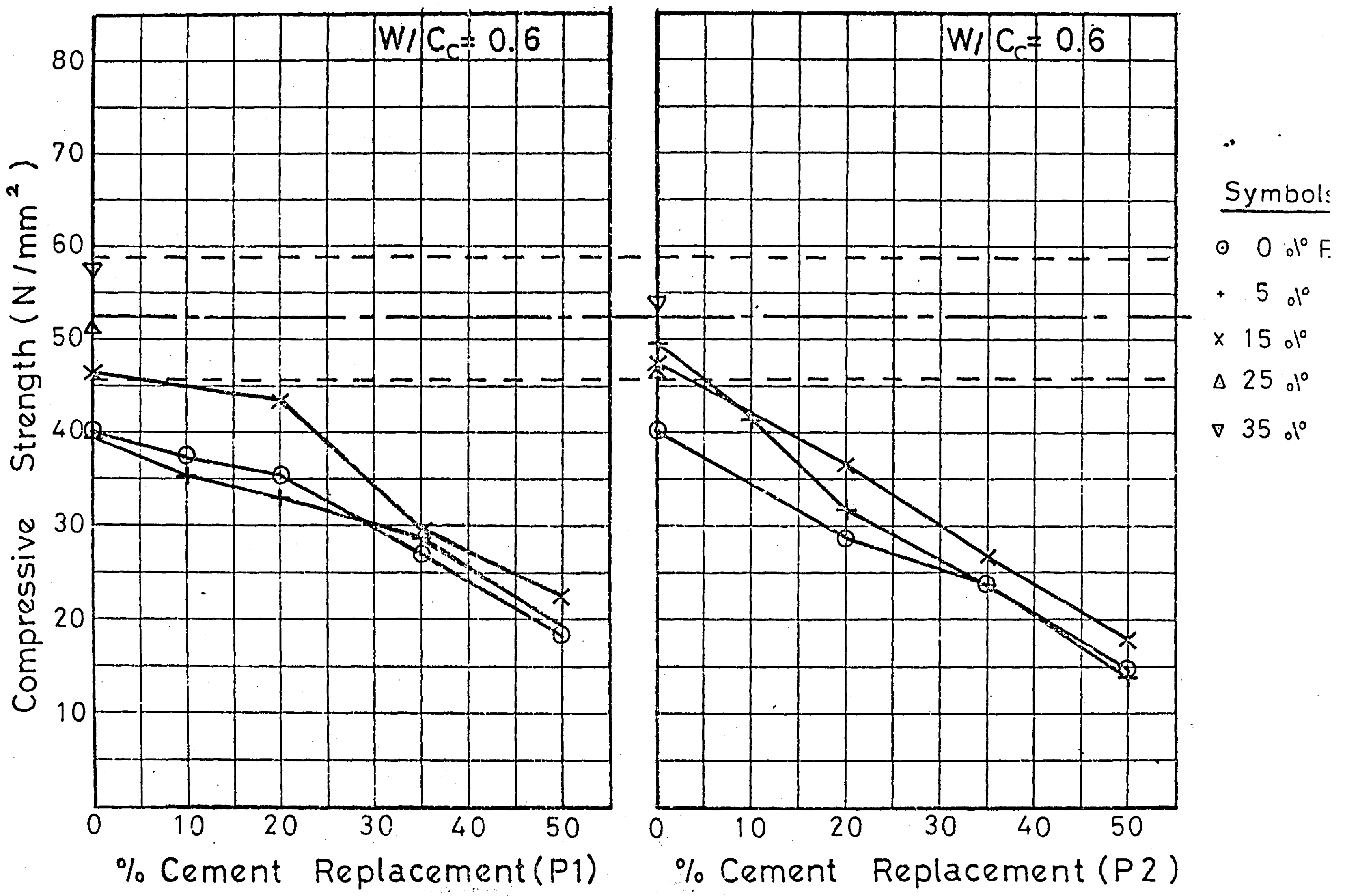
G.8.3.3.6 28 Day Compressive Strength v. % Cement Replacement



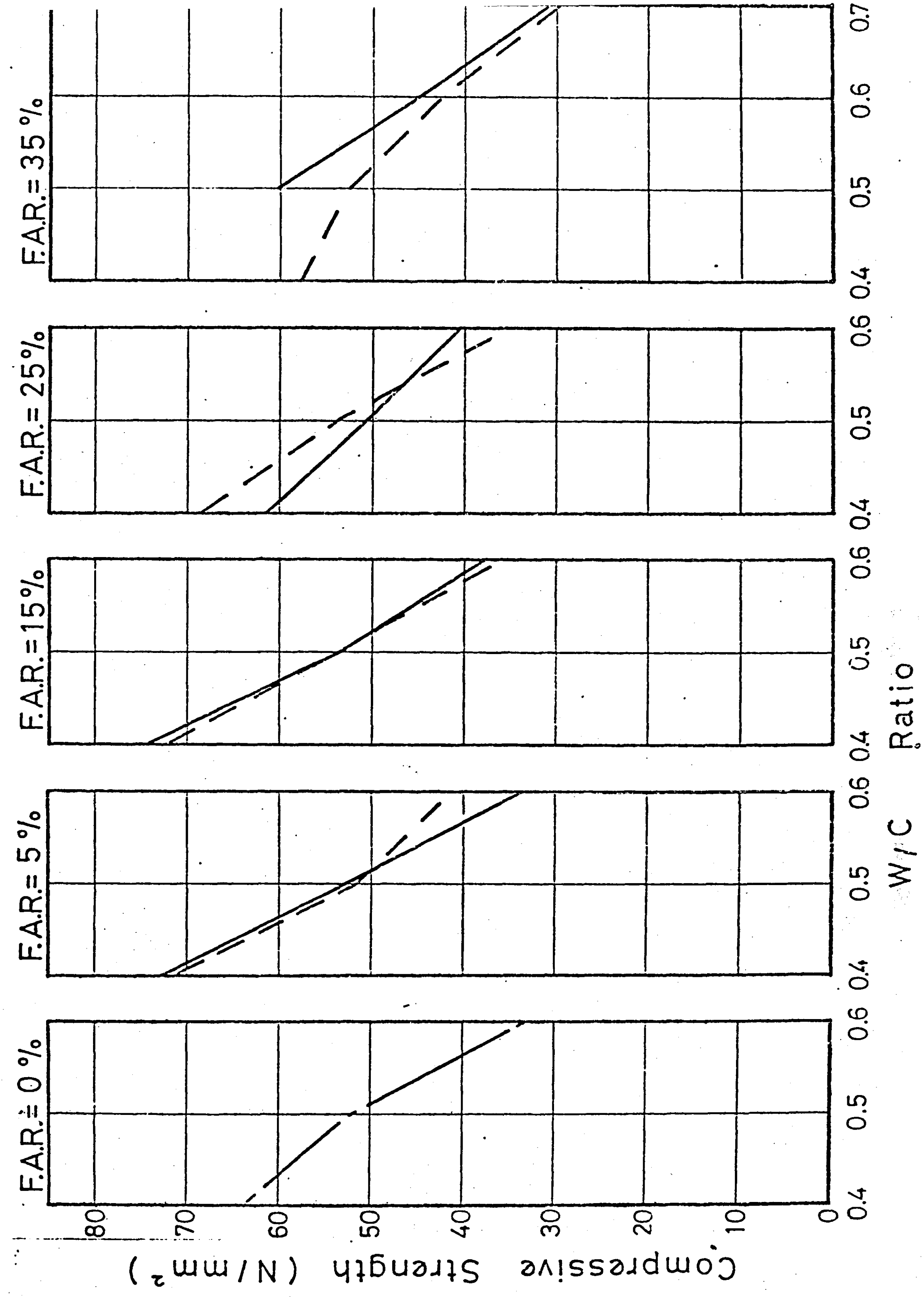
G.8.3.3.7 91 Day Compressive Strength v. % Cement Replacement



G.8.3.3.8 91 Day Compressive Strength v. % Cement Replacement



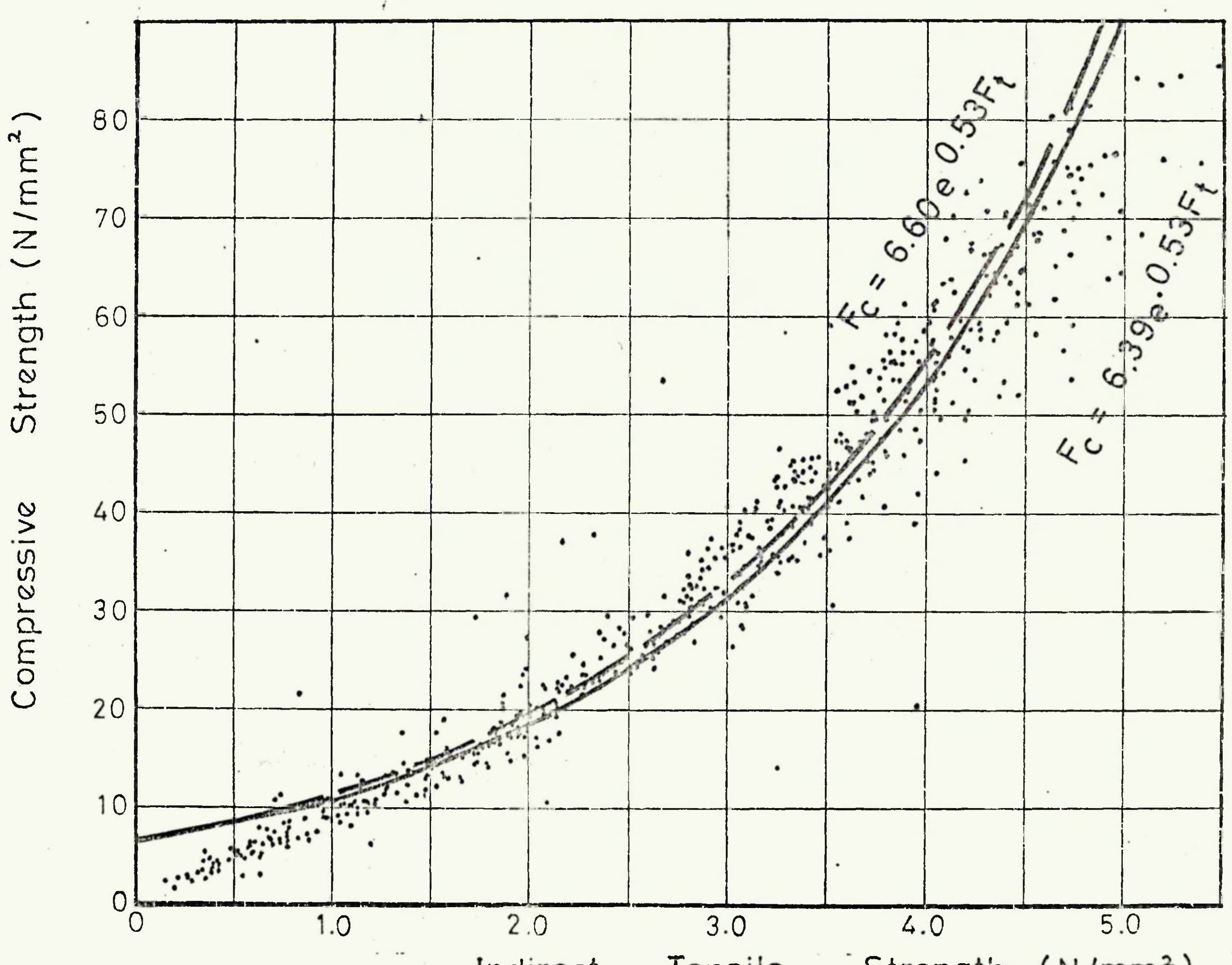
G.8.3.3.9 91 Day Compressive Strength v. % Cement Replacement



G.8.3.4 28 Day Compressive Strength v. W/C Ratio, 0 - 35% F.A.R.

G.8.3.5.1

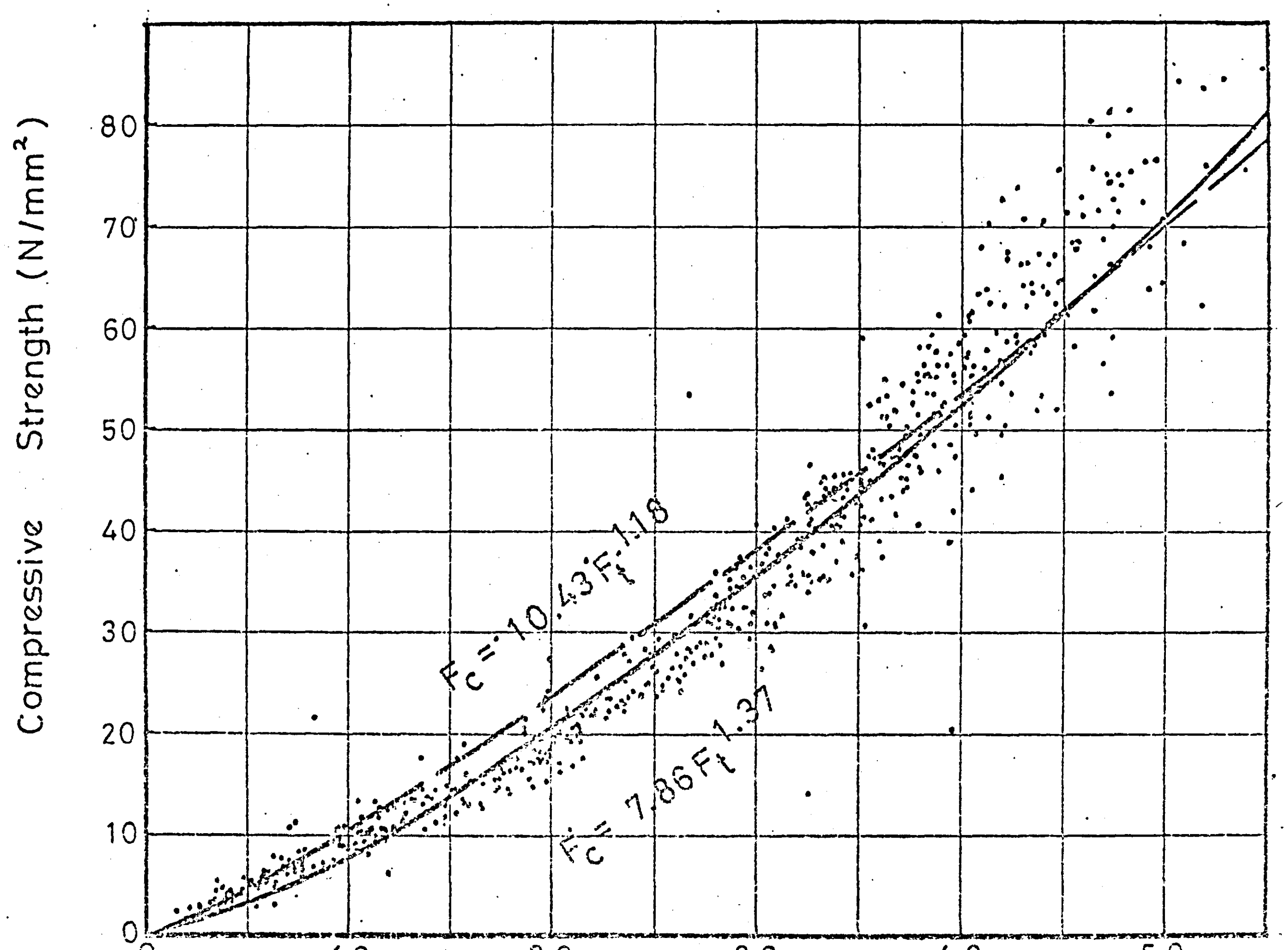
'Exponential' law



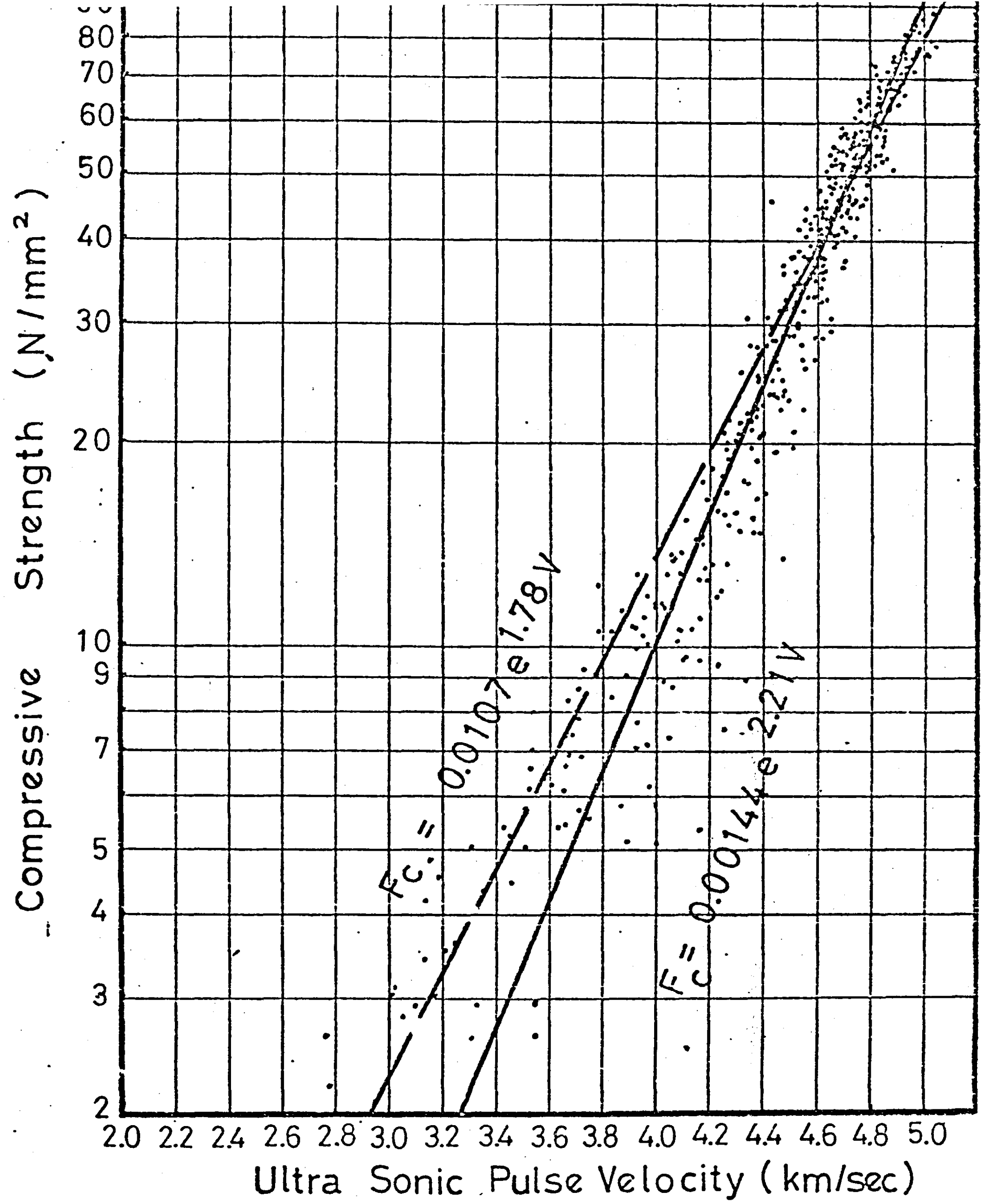
Compressive Strength v. Indirect Tensile Strength

G.8.3.5.2

'Power' law



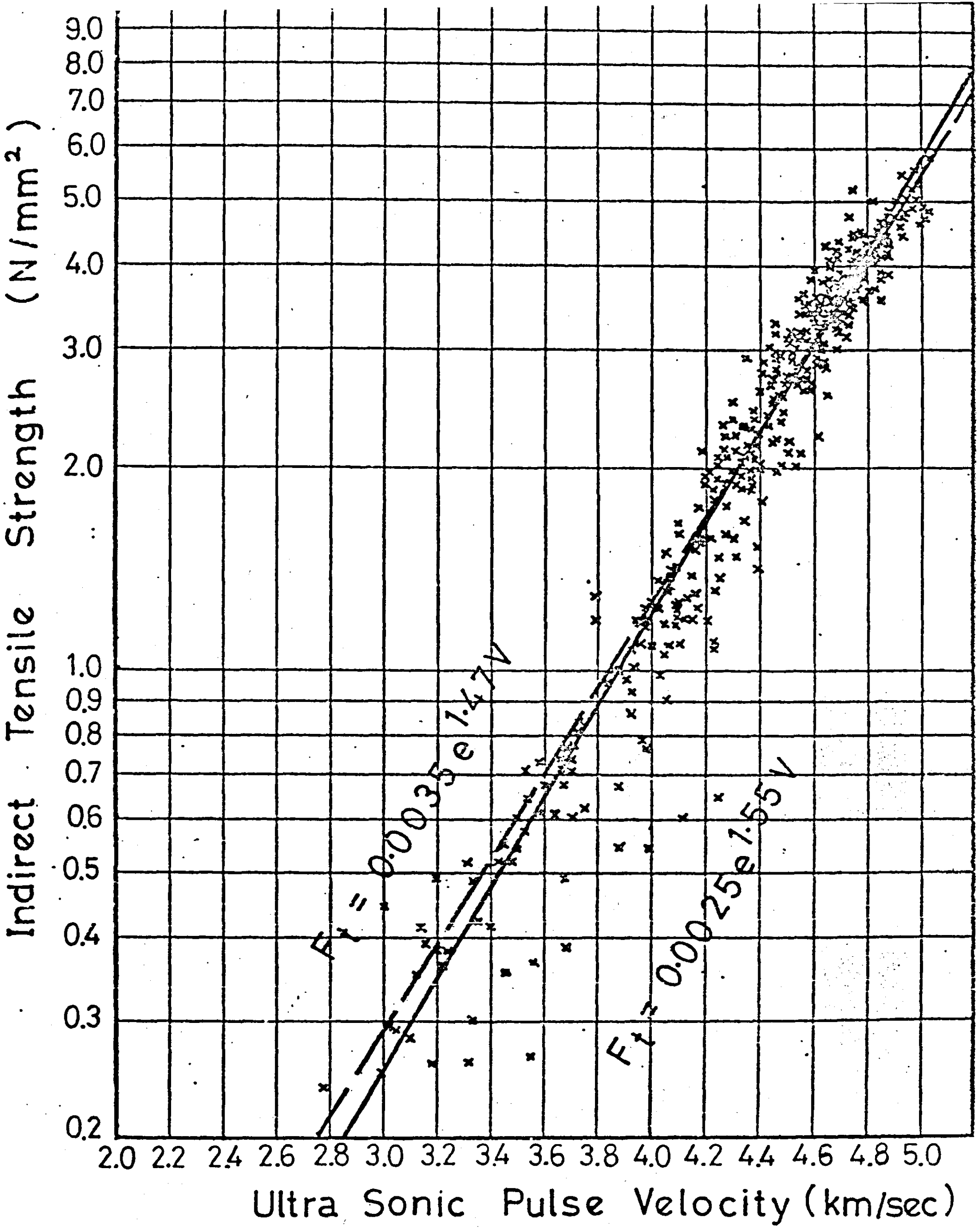
Compressive Strength v. Indirect Tensile Strength



Compressive Strength v. Ultra Sonic Pulse Velocity

G.8.3.5.3

—— All mixes — — Control mixes



Indirect Tensile Strength v. Ultra Sonic Pulse Velocity

G.8.3.5.4

——— All mixes　　— — — Control mixes

8.3.6 Tables of correlation coefficients - properties of hardened concrete v mix constituents.

CORRELATION COEFFICIENTS

P1/-/40

7 Days

	CEMENT	POZZ.	FINE AGG.	COMP. STR.	IND. TEN. STR.	U.S.P.V.	CUBE WT.
CEMENT	1.00	-0.61	-0.24	0.97	0.92	0.91	0.48
POZZOLAN	-0.61	1.00	-0.63	-0.70	-0.49	-0.61	-0.71
FINE AGG.	-0.24	-0.63	1.00	-0.09	-0.30	-0.14	0.39
COMP. STR.	0.97	-0.70	-0.09	1.00	0.89	0.92	0.52
IND TEN STR	0.92	-0.49	0.30	0.89	1.00	0.88	0.35
U.S.P.V.	0.91	-0.61	-0.14	0.92	0.88	1.00	0.40
CUBE WT.	0.48	-0.71	0.39	0.52	0.35	0.40	1.00

28 Days

	CEMENT	POZZ.	FINE AGG.	COMP. STR.	IND. TEN. STR.	U.S.P.V.	CUBE WT.
CEMENT	1.00	-0.61	-0.24	0.92	0.93	0.94	0.76
POZZOLAN	-0.61	1.00	-0.63	-0.75	-0.54	-0.74	-0.91
FINE AGG.	-0.23	-0.63	1.00	0.02	-0.25	-0.01	0.36
COMP. STR.	0.92	-0.75	0.02	1.00	0.87	0.89	0.88
IND TEN STR	0.93	-0.54	-0.25	0.87	1.00	0.87	0.64
U.S.P.V.	0.94	-0.74	-0.01	0.89	0.87	1.00	0.78
CUBE WT.	0.76	-0.91	0.36	0.88	0.64	0.78	1.00

91 Days

	CEMENT	POZZ.	FINE AGG.	COMP. STR.	IND. TEN. STR.	U.S.P.V.	CUBE WT.
CEMENT	1.00	-0.61	-0.24	0.90	0.83	0.94	0.83
POZZOLAN	-0.61	1.00	-0.63	-0.65	-0.42	-0.70	-0.91
FINE AGG.	-0.24	-0.63	1.00	-0.09	-0.30	-0.07	-0.31
COMP. STR.	0.90	-0.65	-0.09	1.00	0.73	0.92	0.77
IND TEN STR	0.83	-0.42	-0.30	0.73	1.00	0.88	0.67
U.S.P.V.	0.94	-0.70	-0.07	0.92	0.88	1.00	0.88
CUBE WT.	0.83	-0.91	0.31	0.77	0.67	0.88	1.00

CORRELATION COEFFICIENTS

P2/-/40

7 Days

	CEMENT	POZZ.	FINE AGG.	COMP. STR.	IND. TEN. STR.	U.S.P.V.	CUBE WT.
CEMENT	1.00	-0.41	-0.40	0.97	0.95	0.91	0.09
POZZOLAN	-0.41	1.00	-0.67	-0.49	-0.42	-0.67	-0.84
FINE AGG.	-0.40	-0.67	1.00	-0.30	-0.35	-0.06	0.76
COMP. STR.	0.97	-0.49	-0.30	1.00	0.97	0.94	0.20
IND TEN STR	0.95	-0.42	-0.35	0.97	1.00	0.89	0.13
U.S.P.V.	0.91	-0.67	-0.06	0.94	0.89	1.00	0.36
CUBE WT.	0.09	-0.84	0.76	0.20	0.13	0.36	1.00

28 Days

	CEMENT	POZZ.	FINE AGG.	COMP. STR.	IND. TEN. STR.	U.S.P.V.	CUBE WT.
CEMENT	1.00	-0.41	-0.40	0.95	0.91	0.87	0.32
POZZOLAN	-0.41	1.00	-0.67	-0.59	-0.59	-0.76	-0.82
FINE AGG.	-0.40	-0.67	1.00	-0.18	-0.15	0.05	0.57
COMP. STR.	0.95	-0.59	-0.18	1.00	0.98	0.93	0.53
IND TEN STR	0.91	-0.59	-0.15	0.98	1.00	0.91	0.53
U.S.P.V.	0.87	-0.76	0.05	0.93	0.91	1.00	0.67
CUBE WT.	0.32	-0.82	0.57	0.53	0.53	0.67	1.00

91 Days

	CEMENT	POZZ.	FINE AGG.	COMP. STR.	IND. TEN. STR.	U.S.P.V.	CUBE WT.
CEMENT	1.00	-0.41	-0.40	0.89	0.93	0.84	0.06
POZZOLAN	-0.41	1.00	-0.67	-0.57	-0.40	-0.62	-0.76
FINE AGG.	-0.40	-0.67	1.00	-0.15	-0.35	-0.06	0.712
COMP. STR.	0.89	-0.57	-0.15	1.00	0.91	0.85	0.39
IND TEN STR	0.93	-0.40	-0.35	0.91	1.00	0.82	0.22
U.S.P.V.	0.84	-0.62	-0.06	0.85	0.82	1.00	0.42
CUBE WT.	0.06	-0.76	0.71	0.39	0.22	0.42	1.00

CORRELATION COEFFICIENTS

P1/-/50

7 Days

	CEMENT	POZZ.	FINE AGG.	COMP. STR.	IND. TEN. STR.	U.S.P.V.	CUBE WT.
CEMENT	1.00	-0.57	0.05	0.81	0.85	0.56	0.64
POZZOLAN	-0.57	1.00	-0.84	-0.30	-0.39	-0.17	-0.68
FINE AGG.	0.05	-0.84	1.00	-0.16	-0.06	-0.12	0.44
COMP. STR.	0.81	-0.30	-0.16	1.00	0.99	0.67	0.65
IND TEN STR	0.85	-0.39	-0.06	0.99	1.00	0.69	0.69
U.S.P.V.	0.56	-0.17	-0.12	0.67	0.69	1.00	0.41
CUBE WT.	0.64	-0.68	0.44	0.64	0.69	0.41	1.00

28 Days

	CEMENT	POZZ.	FINE AGG.	COMP. STR.	IND. TEN. STR.	U.S.P.V.	CUBE WT.
CEMENT	1.00	-0.57	0.05	0.86	0.83	0.87	0.80
POZZOLAN	-0.57	1.00	-0.84	-0.24	-0.26	-0.58	-0.83
FINE AGG.	0.05	-0.84	1.00	-0.22	-0.19	0.18	0.53
COMP. STR.	0.86	-0.24	-0.22	1.00	0.97	0.79	0.65
IND TEN STR	0.83	-0.26	-0.19	0.97	1.00	0.79	0.65
U.S.P.V.	0.87	-0.58	0.18	0.79	0.79	1.00	0.83
CUBE WT.	0.80	-0.83	0.53	0.65	0.65	0.83	1.00

91 Days

	CEMENT	POZZ.	FINE AGG.	COMP. STR.	IND. TEN. STR.	U.S.P.V.	CUBE WT.
CEMENT	1.00	-0.57	0.05	0.83	0.60	0.83	0.81
POZZOLAN	-0.57	1.00	-0.84	-0.18	-0.05	-0.47	-0.71
FINE AGG.	0.05	-0.84	1.00	-0.26	-0.29	0.08	0.39
COMP. STR.	0.83	-0.18	-0.26	1.00	0.83	0.75	0.68
IND TEN STR	0.60	-0.05	-0.29	0.83	1.00	0.72	0.62
U.S.P.V.	0.83	-0.47	0.08	0.75	0.72	1.00	0.79
CUBE WT.	0.81	-0.71	0.39	0.68	0.62	0.74	1.00

CORRELATION COEFFICIENTS

P2/-/50

7 Days

	CEMENT	POZZ.	FINE AGG.	COMP. STR.	IND. TEN. STR.	U.S.P.V.	CUBE WT.
CEMENT	1.00	-0.56	0.03	0.96	0.92	0.95	0.69
POZZOLAN	-0.56	1.00	-0.84	-0.56	-0.63	-0.67	-0.94
FINE AGG.	0.03	-0.84	1.00	0.06	0.16	0.20	0.68
COMP. STR.	0.96	-0.56	0.06	1.00	0.98	0.91	0.70
IND TEN STR	0.92	-0.63	0.16	0.98	1.00	0.89	0.74
U.S.P.V.	0.95	-0.67	0.20	0.91	0.89	1.00	0.79
CUBE WT.	0.69	-0.94	0.68	0.70	0.74	0.79	1.00

28 Days

	CEMENT	POZZ.	FINE AGG.	COMP. STR.	IND. TEN. STR.	U.S.P.V.	CUBE WT.
CEMENT	1.00	-0.56	0.03	0.99	0.94	0.93	0.70
POZZOLAN	-0.56	1.00	-0.84	-0.54	-0.54	-0.75	-0.91
FINE AGG.	0.03	-0.84	1.00	0.01	0.05	0.30	0.64
COMP. STR.	0.99	-0.54	0.01	1.00	0.96	0.92	0.69
IND TEN STR	0.94	-0.54	0.05	0.96	1.00	0.90	0.70
U.S.P.V.	0.93	-0.75	0.30	0.92	0.90	1.00	0.86
CUBE WT.	0.70	-0.91	0.64	0.69	0.70	0.86	1.00

91 Days

	CEMENT	POZZ.	FINE AGG.	COMP. STR.	IND. TEN. STR.	U.S.P.V.	CUBE WT.
CEMENT	1.00	-0.56	0.03	0.98	0.95	0.93	0.71
POZZOLAN	-0.56	1.00	-0.84	-0.46	-0.42	-0.72	-0.92
FINE AGG.	0.03	-0.84	1.00	-0.09	-0.11	0.26	0.65
COMP. STR.	0.98	-0.46	-0.09	1.00	0.98	0.88	0.62
IND TEN STR	0.95	-0.42	-0.11	0.98	1.00	0.84	0.58
U.S.P.V.	0.93	-0.72	0.26	0.88	0.84	1.00	0.82
CUBE WT.	0.71	-0.92	0.65	0.62	0.58	0.82	1.00

CORRELATION COEFFICIENTS

PROPORTIONS & QUALITY

P1/-/60

7 Days

	CEMENT	POZZ.	FINE AGG.	COMP. STR.	IND. TEN. STR.	U.S.P.V.	CUBE WT.
CEMENT	1.00	-0.37	-0.38	0.94	0.95	0.93	0.21
POZZOLAN	-0.37	1.00	-0.72	-0.72	-0.18	-0.30	-0.46
FINE AGG.	-0.38	-0.72	1.00	-0.63	-0.53	-0.41	-0.16
COMP. STR.	0.94	-0.02	-0.63	1.00	0.98	0.91	0.68
IND TEN STR	0.95	-0.18	-0.53	0.98	1.00	0.94	0.71
U.S.P.V.	0.98	-0.30	-0.41	0.91	0.94	1.00	0.82
CUBE WT.	0.81	-0.46	-0.16	0.68	0.71	0.82	1.00

28 Days

	CEMENT	POZZ.	FINE AGG.	COMP. STR.	IND. TEN. STR.	U.S.P.V.	CUBE WT.
CEMENT	1.00	-0.37	-0.38	0.95	0.94	0.95	0.55
POZZOLAN	-0.37	1.00	0.72	-0.09	-0.22	-0.31	-0.68
FINE AGG.	-0.38	-0.72	1.00	-0.62	-0.49	-0.40	0.27
COMP. STR.	0.95	-0.09	-0.62	1.00	0.95	0.93	0.35
IND TEN STR	0.94	-0.22	-0.49	0.95	1.00	0.93	0.44
U.S.P.V.	0.95	-0.31	-0.4	0.93	0.93	1.00	0.51
CUBE WT.	0.55	-0.68	-0.26	0.35	0.44	0.51	1.00

91 Days

	CEMENT	POZZ.	FINE AGG.	COMP. STR.	IND. TEN. STR.	U.S.P.V.	CUBE WT.
CEMENT	1.00	-0.37	-0.38	0.90	0.84	0.81	0.84
POZZOLAN	-0.37	1.00	-0.72	0.031	-0.076	-0.25	-0.49
FINE AGG.	-0.38	-0.72	1.00	-0.70	-0.55	-0.37	-0.15
COMP. STR.	0.90	0.03	-0.70	1.00	0.92	0.76	0.66
IND TEN STR	0.81	-0.08	-0.55	0.92	1.00	0.63	0.53
U.S.P.V.	0.81	-0.25	-0.37	0.76	0.63	1.00	0.75
CUBE WT.	0.84	-0.49	-0.15	0.66	0.53	0.75	1.00

CORRELATION COEFFICIENTS

P2/-/60

7 Days

	CEMENT	POZZ.	FINE AGG.	COMP. STR.	IND. TEN. STR.	U.S.P.V.	CUBE WT.
CEMENT	1.00	-0.38	-0.47	0.97	0.98	0.91	0.54
POZZOLAN	-0.38	1.00	-0.64	-0.22	-0.28	-0.37	-0.86
FINE AGG.	-0.47	-0.64	1.00	-0.60	-0.54	-0.40	0.37
COMP. STR.	0.97	-0.22	-0.60	1.00	0.98	0.86	0.45
IND TEN STR	0.98	-0.28	-0.54	0.98	1.00	0.87	0.43
U.S.P.V.	0.91	-0.37	-0.40	0.86	0.87	1.00	0.63
CUBE WT.	0.54	-0.86	0.37	0.45	0.49	0.63	1.00

28 Days

	CEMENT	POZZ.	FINE AGG.	COMP. STR.	IND. TEN. STR.	U.S.P.V.	CUBE WT.
CEMENT	1.00	-0.38	- 0.47	0.98	0.99	0.97	0.69
POZZOLAN	-0.38	1.00	-0.64	-0.32	-0.36	-0.44	-0.75
FINE AGG.	-0.47	-0.64	1.00	-0.51	-0.47	-0.39	0.15
COMP. STR.	0.98	-0.32	-0.51	1.00	0.97	0.92	0.69
IND TEN STR	0.99	-0.36	-0.47	0.97	1.00	0.95	0.67
U.S.P.V.	0.97	-0.44	-0.39	0.92	0.95	1.00	0.71
CUBE WT.	0.69	-0.75	0.15	0.69	0.67	0.71	1.00

91 Days

	CEMENT	POZZ.	FINE AGG.	COMP. STR.	IND. TEN. STR.	U.S.P.V.	CUBE WT.
CEMENT	1.00	-0.38	-0.47	0.98	0.95	0.95	0.73
POZZOLAN	-0.38	1.00	-0.64	-0.23	-0.32	-0.40	-0.70
FINE AGG.	-0.47	-0.64	1.00	-0.59	-0.48	-0.41	0.06
COMP. STR.	0.98	-0.23	-0.59	1.00	0.97	0.90	0.70
IND TEN STR	0.95	-0.32	-0.48	0.97	1.00	0.89	0.80
U.S.P.V.	0.95	-0.40	-0.41	0.90	0.89	1.00	0.75
CUBE WT.	0.73	-0.70	0.06	0.67	0.80	0.75	1.00

8.4 Durability Test

comprising tables:-

T. 8.4.1.O

T. 8.4.1.1A - C.

N.B. For details of test see 6.5.3. and 9.4.1.

DURABILITY (Immersion in $MgSO_4$)

CONTROL

NO.	MIX CODE	WT. CHANGE (kg.)	% WT. CHANGE	NO.	MIX CODE	WT. CHANGE (kg.)	% WT. CHANGE
2	00/00/50	+0.032	+1.29				
16	"	-	-				
17	"	-	-				
33	"	+0.007	+0.28				
37	"	+0.012	+0.51				
38	"	+0.010	+0.39				
52	"	+0.023	+0.94				
53	"	+0.018	+0.75				
54	"	+0.022	+0.91				
65	"	+0.013	+0.53				
104	"	+0.017	+0.69				
105	"	+0.032	+1.32				
	Mean		0.761				
	Std. Dev.		0.355				
*	90%L.C.L.	'Control'	+0.17				
*	90%L.C.L.	'General'	-2.11				

* 90% L.C.L. equivalent to 90% Lower Confidence Limit.

T. 8.4.1.1 Table of mixes with % weight loss greater than 1.64s from mean ($\bar{x}$) - based on 'Control' and 'General' % weight loss.

N.B. Exceeding 90% L.C.L. 'Control' - Yellow

Exceeding 90% L.C.L. 'General' - Red

P1-2/-/40

NO.	MIX CODE	WT. CHANGE (kg.)	% WT. CHANGE	NO.	MIX CODE	WT. CHANGE (kg.)	% WT. CHANGE
1	00/00/40	+0.017	+0.67	1	00/00/40	+0.017	+0.67
18	P100/05/40	-0.020	-0.81	36	P200/05/40	+0.003	+0.13
13	P100/15/40	+0.002	+0.08	10	P200/15/40	+0.015	+0.59
6	P100/25/40	-0.043	-1.73	7	P200/25/40	-0.010	-0.42
-	P100/35/40	-	-	79	P200/35/40	-0.018	-0.83
28	P110/00/40	-0.002	-0.08	26	P210/00/40	-0.004	-0.15
29	P110/05/40	-0.003	-0.11	27	P210/05/40	-0.005	-0.22
-	P110/15/40	-	-	-	P210/15/40	-	-
-	P110/25/40	-	-	--	P210/25/40	-	-
-	P110/35/40	-	-	-	P210/35/40	-	-
41	P120/00/40	-0.009	-0.36	46	P220/00/40	+0.007	+0.28
42	P120/05/40	+0.018	+0.75	49	P220/05/40	+0.019	+0.77
85	P120/15/40	+0.009	+0.39	94	P220/15/40	-0.051	-2.21
-	P120/25/40	-	-	-	P220/25/40	-	-
-	P120/35/40	-	-	-	P220/35/40	-	-
66	P135/00/40	+0.000	+0.01	71	P235/00/40	+0.007	+0.29
75	P135/05/40	-0.001	-0.03	76	P235/05/40	+0.010	+0.42
91	P135/15/40	+0.009	+0.37	95	P235/15/40	-0.000	-0.02
-	P135/25/40	-	-	-	P235/25/40	-	-
-	P135/35/40	-	-	-	P235/35/40	-	-
56	P150/00/40	-0.011	-0.45	60	P250/00/40	-0.002	-0.08
-	P150/05/40	-	-	61	P250/05/40	-0.000	-0.01
97	P150/15/40	-0.053	-2.22	101	P250/15/40	-0.007	-0.29
-	P150/25/40	-	-	-	P250/25/40	-	-
-	P150/35/40	-	-	-	P250/35/40	-	-

DURABILITY (Immersion in $MgSO_4$)

P1-2/-/50

NO.	MIX CODE	WT. CHANGE (kg.)	% WT. CHANGE	NO.	MIX CODE	WT. CHANGE (kg.)	% WT. CHANGE
C	00/00/50			C	00/00/50		
19	P100/05/50	+0.009	+0.38	35	P200/05/50	+0.024	+0.97
14	P100/15/50	+0.015	+0.62	11	P200/15/50	+0.010	+0.41
4	P100/25/50	+0.017	+0.48	8	P200/25/50	+0.016	+0.66
83	P100/35/50	-0.000	-0.02	80	P200/35/50	+0.006	+0.27
21	P110/00/50	+0.012	+0.48	24	P210/00/50	+0.017	+0.71
22	P110/05/50	+0.008	+0.32	25	P210/05/50	+0.022	+0.91
-	P110/15/50	-	-	-	P210/15/50	-	-
107	P110/25/50	+0.012	+0.47	-	P210/25/50	-	-
-	P110/35/50	-	-	-	P210/35/50	-	-
39	P120/00/50	+0.014	+0.56	47	P220/00/50	+0.018	+0.73
43	P120/05/50	+0.007	+0.28	51	P220/05/50	+0.019	+0.79
86	P120/15/50	-0.016	-0.68	89	P220/15/50	+0.008	+0.33
116	P120/25/50	+0.013	+0.56	115	P220/25/50	+0.014	+0.61
-	P120/35/50	-	-	-	P220/35/50	-	-
67	P135/00/50	-0.004	-0.18	70	P235/00/50	+0.019	+0.77
74	P135/05/50	+0.005	+0.19	77	P235/05/50	-0.007	-0.29
92	P135/15/50	+0.009	+0.40	96	P235/15/50	+0.002	+0.08
106	P135/25/50	+0.013	+0.54	113	P235/25/50	+0.009	+0.36
109	P135/35/50	+0.006	+0.25	111	P235/35/50	+0.007	+0.32
55	P150/00/50	-0.088	-3.66	59	P250/00/50	-	-
-	P150/05/50	-	-	62	P250/05/50	+0.004	+0.18
98	P150/15/50	+0.002	+0.08	102	P250/15/50	-0.012	-0.53
108	P150/25/50	-0.015	-0.64	114	P250/25/50	-0.000	-0.02
110	P150/35/50	+0.004	+0.17	112	P250/35/50	+0.003	+0.15

P1-2/-/60

NO.	MIX CODE	WT. CHANGE (kg.)	% WT. CHANGE	NO.	MIX CODE	WT. CHANGE (kg.)	% WT. CHANGE
3	00/00/60	+0.001	+0.04	3	00/00/60	+0.001	+0.04
20	P100/05/60	+0.012	+0.50	34	P200/05/60	+0.026	+1.08
15	P100/15/60	+0.008	+0.32	12	P200/15/60	+0.026	+1.11
5	P100/25/60	-0.006	-0.25	9	P200/25/60	+0.025	+1.06
84	P100/35/60	-0.001	-0.04	81	P200/35/60	-0.024	-1.03
31	P110/00/60	-	-	-	P210/00/60	-	-
30	P110/05/60	+0.008	+0.32	32	P210/05/60	+0.030	+1.28
-	P110/15/60	-	-	-	P210/15/60	-	-
-	P110/25/60	-	-	-	P210/25/60	-	-
-	P110/35/60	-	-	-	P210/35/60	-	-
40	P120/00/60	+0.018	+0.77	48	P220/00/60	+0.001	+0.03
44	P120/05/60	+0.003	+0.13	50	P220/05/60	+0.021	+0.89
88	P120/15/60	+0.008	+0.36	90	P220/15/60	+0.014	+0.60
-	P120/25/60	-	-	-	P220/25/60	-	-
-	P120/35/60	-	-	-	P220/35/60	-	-
68	P135/00/60	+0.023	+1.24	69	P235/00/60	-0.008	-0.02
73	P135/05/60	+0.018	+0.78	78	P235/05/60	+0.009	+0.40
93	P135/15/60	+0.020	+0.82	99	P235/15/60	+0.009	+0.38
-	P135/25/60	-	-	-	P235/25/60	-	-
-	P135/35/60	-	-	-	P235/35/60	-	-
57	P150/00/60	-0.200	-8.53	58	P250/00/60	+0.010	+0.44
-	P150/05/60	-	-	63	P250/05/60	-0.006	-0.27
100	P150/15/60	-0.179	-7.59	103	P250/15/60	-0.034	-1.50
-	P150/25/60	-	-	-	P250/25/60	-	-
-	P150/35/60	-	-	-	P250/35/60	-	-

CHAPTER 9

DISCUSSION OF RESULTS AND SUMMARY CONCLUSIONS

9.0 Discussion of Results and Summary Conclusions

9.1 Introduction

The first part of this chapter deals with the relationships between mix constituents, properties and workability in terms of the compacting factor test. It is followed by an appraisal of the interrelationships between all workability tests which comprise slump, compacting factor, VeBe and 2 point test.

The second part examines and discusses the significance of control limits applied to each strength test in terms of the age of test. This is followed by an examination of the relationships between mix constituent properties and strength as measured by the compressive strength test. This section concludes with an appraisal of the interrelationships between the principal testing methods employed to assess strength together with the correlation between the above and mix constituent properties at different ages.

The final part of this chapter is concerned with the influence of mix constituent properties upon the durability of concrete as measured by the % weight loss of specimens stored in magnesium sulphate solution.

All section headings in Chapter 9 contain references to the appropriate graphs and tables in Chapter 8 and elsewhere in the text where these are relevant to the discussion.

9.2 Workability

9.2.1 Introduction

The compacting factor test was chosen as that most likely to represent the most useful workability characteristics of fresh concrete and values of compacting factor have been plotted against mixes of various % cement replacements (C.R.) and of various % fine aggregate replacements (F.A.R.) for several water:cement (W/C_c) ratios using both the treated (P 1) and the untreated (P 2) p.f.a. The treated (P 1) and untreated (P 2) have been incorporated by replacing various percentages of cement and fine aggregate with an equivalent volume of P 1 or P 2 in the base concrete mixes. (see 5.3.1.)

For comparison, the results of Slump and VeBe tests are plotted against Compacting Factor on a semilog basis and results of correlations between all four (Slump, Compacting Factor, VeBe and 2 Point) tests are also included.

9.2.2 Compacting Factor (C.F.) v, Cement replacement (C.R.) at different % Fine Aggregate replacement (F.A.R.) levels. (see Graphs G. 8.2.1.1. - 1.3)

9.2.2.1 General

For reference purposes, the author has plotted, upon all graphs, the mean and 90% confidence limits (i.e. $\pm$ 1.64

standard deviations from the mean) of the average control mix which consists of water, cement, fine aggregate and coarse aggregate only with W/C = 0.50 (i.e. containing no p.f.a. material). The compacting factor is the mean of two tests.

$W/_{C_c}$ = 0.40 (G. 8.2.1.1.)

All results fall below the lower 90% control limit however there does appear to be a general tendency for an increase in workability for increasing % C.R. at all % F.A.R. levels for both P 1 and P 2 with P 2 showing slightly higher compacting factors in general especially for large % F.A.R.

$W/_{C_c}$ = 0.50 (G. 8.2.1.2.)

For P 1 there appears to be a workability optimum range (i.e. higher values of C.F.) lying within the 90% control limits for C.R. = 10% and 35% for most F.A.R.s. This is reflected to some extent in the corresponding values for P 2 at 0 and 5% F.A.R. but not at 15 - 35% F.A.R.

In general, at a given % F.A.R. the compacting factors for P 1 are higher than or equal to the corresponding ones for P 2. In addition, the graph indicates that compacting factors can be maintained within the 90% control limits of the control mix up to 25 F.A.R. for P 1 but for only 15% F.A.R. with P 2.

For a given cement replacement increasing F.A.R. reduces the compacting factor for both P 1 and P 2, however, the reduction is more enhanced with P 2 than with P 1 especially for F.A.R. greater than 5%

$W/_{C_c}$ = 0.60 (G. 8.2.1.3.)

All compacting factors are too close to 1.00 for any realistic inference to be drawn except that no improvement in workability is evident after a cement replacement of 10% has been reached and further that the effect of F.A.R. has little effect upon values of C.F.

9.2.2.2. Discussion

Venuat (18) showed that workability (as measured by the flow table) was enhanced up to a certain % C.R. by weight whereupon it decreased. He concluded further that the effectiveness of p.f.a. upon the workability increased as the mix became more dry.

Jolly (21) showed that for mixes with high cement content and low water/cement ratios the workability reduced with increase in p.f.a. In lean mixes however he found that the converse was the case. He suggested that this was due to the lubrication effect of the spherical particles of p.f.a.

The author considers that there are three major factors influencing these workability measurements, which all influence the water demand of the p.f.a. concrete.

i) The relative specific surfaces of the cement, p.f.a. (P 1 and P 2) and fine aggregate.

ii) The particle shapes of the cement, p.f.a. (P 1 and P 2) and fine aggregate.

iii) The absorption capacity of the cement, p.f.a., and fine aggregate.

The relative dominance of i), ii) and iii) appears to be determined by the % replacement level, the type of material being replaced and the water content (W/C_c) of the mix.

In the work being discussed the relative influences can be summarised as follows:-

(a) For cement replacement only, ii) appears to dominate since the specific surfaces of the cement and p.f.a. are of a comparable nature therefore the water demand of the mix decreases as the result of the spherical shape of the p.f.a. particles.

(b) For fine aggregate replacement only it is probable that ii) has a larger influence at low levels of F.A.R. due to lubricating effect of the spherical particles referred to in (a). As the F.A.R. increases (15% and above) the water demand of the replacement material i.e. i) and iii) prevail since the p.f.a., as indicated by Graph G. 4.3.2.

is likely to have a much larger specific surface than the fine aggregate which it replaces.

(c) For combined cement and fine aggregate replacement the effect of iii) becomes more apparent as the % C.R. increases and the compacting factors of P 2 mixes (high absorption probably due to larger % of carbonaceous material; see T. 4.3.2. C) decrease relative to those of the corresponding P 1 mixes.

Previous work has indicated (25) that the carbon content (related to ignition loss) has an appreciable effect upon the water demand and hence workability of p.f.a. concretes. Increased carbon content leads to a decrease in workability for a given water content. In addition, the % passing the No. 325 sieve (26) also affects workability through its influence upon the water demand. These factors have been discussed previously.

Whilst bearing in mind the above factors, the author's conclusions based upon his own findings from experimental work presented in graphs G. 8.2.1.1. - 3 are as follows:-

i) At medium water contents ($W/_{C_c}$ = 0.50) increasing % C.R. at F.A.R. up to 25% leads to an increase in workability for Pozz. 1 mixes and holds to a lesser extent with Pozz. 2 mixes up to a F.A.R. of 15%.

ii) At low water contents ($W/_{C_c}$ = 0.40) workability generally increases slightly for increasing C.R. but decreases as F.A.R. increases above 5% for both P 1 and P 2 mixes. P 2 mixes display slightly higher workability values than the corresponding P 1 mixes.

iii) At high water contents ($W/_{C_c}$ = 0.60) workability increases slightly for 10% C.R. but changes little above this level. For low C.R. the workability was increased slightly for F.A.R. around 15% but returned to control levels above this level. As C.R. increased the effect of F.A.R. was reduced.

iv) For medium water contents ($W/_{C_c}$ = 0.50)

F.A.R. appears to have a more dramatic effect upon workability than C.R.

v) High % F.A.R. appears to be more beneficial for workability using Pozz. 1 than Pozz. 2 at medium water contents (W/C_c = 0.50).

9.2.3 Sensitivity and limitations of workability tests (Appendix III)

As mentioned previously, the compacting factor was chosen by the author as the most suitable test for measuring comparative workability of the chosen range of mixes. The reasons for this are as follows:-

i) The coefficient of variation of compacting factor (C.F.) was much smaller than any of the other tests - for the twelve control mixes in the programme. (See Appendix III) Mix Properties - Workability).

ii) The compacting factor is fundamentally less operator sensitive than the other British Standard workability tests.

iii) The compacting factor is a British Standard test and is considered to be the most suitable for site use (62) although in practice not used so extensively as the slump.

iv) By plotting the results of all the workability tests against the mix variables the author considered the compacting factor to be the most sensitive in determining variations in these variables.

The author found that the slump test was extremely operator sensitive even with medium workability mixes. Slumps varying between 5 and 30 mm could be frequently obtained on the same mix. Further evidence of this can be seen from Appendix III where the range of slumps for twelve mixes of nominally identical proportions is 10 - 65 mm.

The VeBe was suitable for medium workability mixes but for very dry mixes excessively long VeBe times because of low paste content led the author to doubt the validity of this test for such concretes. For wet mixes or high workability mixes the determination of the cut off point was difficult to ascertain, bearing in mind the small VeBe times associated with such mixes. In this respect the proportional influence of operator error either in respect of initial compaction or the cut off point (i.e. cessation of vibration) increases as the VeBe time decreases. The average VeBe times for the twelve control mixes was 4.7 secs with a coefficient of variation of 48% this corresponds to a 90% lower confidence limit of 1.0 sec. Bearing in mind what has been previously said in this paragraph the inclusion of this test as a comparative tool was limited in the context of this programme.

The two point test was found by the author to be surprisingly variable in view of its apparent insensitivity to operator performance (See Appendix III Mix properties - Workability). The author also found a considerable number of inexplicable results when values of Yield (Nm) and Slope $(Nms)^{-1}$ (proportional to plastic viscosity) were plotted against mix variables. There are possibly two explanations:-

i) The apparatus was very sensitive to minor random changes in the gradients of fine aggregate and coarse aggregate.

ii) The complexities of particular interaction are more likely to be more manifest in a multiple point viscometer type test than in the British Standard single point type test. (31)

Whatever the true reason for this behaviour, the author feels that in view of the necessary complexity of mixing five constituents (water, cement, p.f.a., fine aggregate, coarse aggregate) as opposed to four in normal concrete a further study of the behaviour of cement/p.f.a./fine aggregate mortar mixes would be advisable before further conclusions can be drawn from these irregular results.

9.2.4 Correlation between workability tests (G. 8.2.2.1./2., T. 8.2.3.)

9.2.4.1 General

Previous work on this subject studied by the author appears to have been directed towards expressing the results from one or two tests in terms of either definable mix parameters e.g. surface index (63) or in terms of a standard single test or its derivatives. (64) (65)

The author has previously expounded his principal reasons for adopting the compacting factor as the chief comparator. This was not through a belief in the fundamental soundness of this test but largely because from the results obtained this appeared to be the best comparator. However, to put the other workability tests into some perspective the author thought that useful background would be provided by obtaining a correlation matrix between all of the tests used.

The equation chosen as the basis was of the form $Y = Ae^{Bx}$.

There are principally two reasons for this:-

i) scalar simplicity in plotting results especially those from Slump and VeBe which have a very large range.

ii) because a function of this form would suffice even if a simple linear relationship existed between two test parameters, without the correlation being necessarily impaired.

The author will restrict his comments principally to the relationship between VeBe v Compacting Factor and Slump v Compacting Factor. The correlation between Yield (Nm) and Slope (reciprocal of plastic viscosity) of the two point test and the British Standard workability tests was poor in general but correlated best with the Compacting Factor (0.69 in each case).

9.2.4.2 <u>VeBe and Slump v Compacting Factor</u>

The results for the VeBe v Compacting Factor and Slump v Compacting Factor have been plotted with their respective functions. These functions are not meant to imply a particular empirical relationship between the tests but are merely plotted as a means for visually comparing the spread of results.

Two interesting points emerge, namely:-

i) The correlation coefficients for the two functions postulated are high for VeBe v Compacting Factor and Slump v Compacting Factor (0.93 and 0.81 respectively).

ii) Despite high correlation there is considerable scatter in each case (G. 8.2.2.1 and G. 8.2.2.2.) which tends to increase as the workability decreases i.e. as the Compacting Factor decreases.

These results tend to confirm the suggestion by Tattersall (34) that the B.S. workability tests are really measuring different properties of the concrete. This disparity appears to be emphasised for low workability concretes. As workability increases, the scatter decreases possibly because factors such as free water content become dominant whereas for drier mixes particle shape, grading and texture prevail.

However, these results in the medium-high workability zones do help to explain why the single point test has maintained its position against more sophisticated attempts to measure workability, as in the majority of cases concretes produced tend to be of medium or high workability.

9.3 Strength Tests

9.3.1 Introduction

Sub-section 9.3.2 deals with the relationship between the properties of hardened concrete and age for the control (00/00/50) mixes only i.e. those mixes containing no Pozz. 1 or 2 and equivalent to Grade 20, medium workability mix from Table 50, CP 110.

Following this in sub-sections 9.3.3. - 9.3.5., the compressive strength test is used to compare the strength properties of the various p.f.a. mixes at various ages with that of the average control mix (00/00/50).

Finally in sub-sections 9.3.6 - 9.3.9. correlations and interrelationships between compressive strength, indirect tensile strength ultra-sonic pulse velocity and mix parameters are suggested and discussed.

9.3.2 Compressive Strength, Indirect Tensile Strength, Ultra-sonic Pulse Velocity, Concrete Density versus Age - Control Mixes Only. (see G. 8.3.1.1.- 1.5)

9.3.2.1 General observations

The mean 1, 7, 14, 28, 91 and 182 day values for the control mix properties have been plotted (continuous line) together with the appropriate 90% (± 1.64 standard deviations) confidence limits. These values are representative of the twelve control mixes produced by the author throughout the mix programme - see Appendix IV for Control results

9.3.2.2 Variation of mean

From graphs G.8.3.1.1-1.3 it can be seen that Compressive Strength, Indirect Tensile Strength and Ultra-sonic pulse velocity all tend to increase with age tending towards a maximum value with increasing age.

The Compressive Strength appears to be more age sensitive than either Indirect Tensile Strength or Ultra-sonic Pulse Velocity at ages above 28 days i.e. the rate of increase in the latter decreases considerably after this point compared with the former.

Concrete density changes very little with Age - see G. 8.3.1.4.

The Coefficient of Variation tends to decrease with increase in Age to a constant value for Compressive Strength, Indirect Tensile Strength, Ultra-sonic Pulse Velocity whilst with Concrete Density once again there is little change.

9.3.2.3. Variation of 90% confidence limits

Graph G.8.3.1.1. shows that 90% confidence limits increase with increasing age for Compressive Strength in contrast with those for Indirect Tensile Strength which except at 14 days remain fairly constant. This 14 day result will be referred to later.

The Ultra-sonic Pulse Velocity 90% confidence limits display a high spread at 1 day but thereafter tend to decrease with age.

9.3.2.4. Coefficient of Variation versus Age

From Graph G. 8.3.1.5. it can be seen that with the exception of Concrete Density versus Age, the Coefficient of Variation for all properties tends to decrease with Age after 1 day. The anomolous increase in the 90% confidence limit value for Indirect Tensile Strength referred to above is reflected in the 14 day Coefficient of Variation for Indirect Tensile Strength also.

For ages up to 28 days the Coefficients of Variation are ranked in the following order:-

Rank of Coefficient of Variation	1 day Coefficient of Variation	Testing Method
1	29.6	Indirect Tensile Strength
2	14.3	Compressive Strength
3	3.6	Ultra-sonic Pulse Velocity
4	0.9	Concrete Density.

It is interesting to note that the Coefficient of Variations of the destructive tests (Compressive and Indirect Tensile Strengths) approach a common value at ages of 28 days and above as do the Coefficients of Variation of the non-destructive tests (Ultra-sonic Pulse Velocity and Concrete Density).

This tends to confirm what one would expect since a destructive test reflects the strength level at which fracture propogates from the weakest point within the specimen whereas non-destructive tests measure properties throughout the whole of the specimen. Variability is likely to be greater in the former case than in the latter.

9.3.2.5 Discussion

Validity of Strength Test

The compressive strength test was chosen for the assessment of strength as it is considered to be

i) sensitive to age over a larger range than the other tests (Indirect Tensile Strength and Ultra-sonic Pulse Velocity)

ii) to have a Coefficient of Variation which is fairly uniform (except at 1 day) at around 7.5% for all ages of test, and

iii) to be the most widely used test for the assessment of the quality of hardened concrete.

Coefficient of Variation versus Age (G. 8.3.1.5.)

The author considers two things worthy of comment here, which are listed as follows:-

i) High coefficient of variation at 1 day.

ii) Anomolous increase in the Coefficient of Variation at 14 days for Indirect Tensile Strength versus Age.

Early age properties of concrete are influenced substantially by temperature and moisture content; the latter depending upon the relative humidity of the environmental curing condition. Whilst every attempt was made by the author to keep these constant in accordance with British Standard conditions, the degree of control in an air environment is more difficult to exercise than in a water cured regime. It is probable therefore that the curing regimes during the initial 24 hours of curing were not identical for successive control mixes which would be reflected in the 1 day results. After 24 hours all specimens were water cured (see sub-section 6.4.9.) hence the lower Coefficient of Variation at later ages. It must be emphasised however that all 1 day specimens were immersed in water at a temperature of 20^{o}C for a period of not less than 2 hours before testing.

The explanation for ii) is more obscure. During the testing of the indirect tensile test cylinders the author noted that at early ages failure occurred primarily because of a rupture in bond at the cement paste/aggregate interface whereas at later ages the fracture propogated indiscriminately through the cement matrix and aggregate with little or no paste/aggregate bond failure. This implies two different failure mechanisms at early and late ages. It further implies a composite failure at intermediate ages; a phenomenon noted by the author. The failure mechanism from subsequent observations (see G. 8.3.5.1./2.) appears to be closely related to the strength of the cement paste which in turn depends upon the maturity and curing conditions.

From the above, the author contends that the mode of failure at 14 days is likely to be a capriciously composite one leading to a high Coefficient of Variation for a series of nominally identical mixes. (See G. 8.3.1.5.)

This change in failure mode could partly explain the bi-functional relationship between compressive strength and indirect tensile strength described later (see G. 8.3.5.1 2)

9.3.3 <u>Compressive Strength versus % Cement replacement with 0% F.A.R. at different ages</u> (See G. 8.3.2.1. - 3.)

9.3.3.1 <u>General Observations</u>

Graph 8.3.2.1. shows that compressive strength (C.S.) generally decreases with increasing % Cement replacement (C.R.) for both Pozz. 1 and Pozz. 2 mixes. However, Pozz. 1 displays a 'strength plateau' i.e. at all W/C_c ratios between 10 and 20% C.R. levels. There is also evidence of a 'plateau' effect with Pozz. 2 but this occurs between 0 and 10% C.R. at later ages and at lower W/C_c ratios. (see Fig. 1)

As W/C_c ratios and age increase, the convexity of the C.S. versus % C.R. curves appears to increase especially with Pozz. 1 mixes.

In general, the compressive strength of Pozz. 1 mixes slightly exceeds that of Pozz. 2 mixes, the difference being in the order of 2 - 10% at 28 days.

At more advanced ages (91 and 182 days) and for W/C_c = 0.40 and 0.50, the 20% C.R. compressive strength exceeds that of the 10% C.R. for Pozz. 1. (See G. 8.3.2.1./2.)

At 50% C.R. the 182 day compressive strength is reduced by approximately 50% of the O.P.C. base mix for higher W/C_c ratios (i.e. W/C_c = 0.50 and 0.60). For lower W/C_c ratios (i.e. W/C_c = 0.40) the corresponding reduction in compressive strength = 30%

The proportional decrease in compressive strength at 1 day decreases as W/C_c is increased for both Pozz. 1 and Pozz. 2 mixes. This effect tends to be reversed with increasing age exemplified by the following figures.

% decrease in strength (0 - 50% C.R.) at 1 day	80	75	60
% decrease in strength (0 - 50% C.R.) at 182 days	30	50	50
W/C_c ratio	0.40	0.50	0.60

9.3.3.2 Discussion

Three principal features emerge from above as follows:-

i) For Pozz. 1 mixes, between 10 - 20% C.R., compressive strength appears to be relatively insensitive to changes in cement replacement (the 'plateau' effect),

ii) There is an increase in convexity of the compressive strength versus % cement replacement with increasing age implying some pozzolanic activity,

iii) At a given % C.R. the % compressive strength loss appears to decrease with decreasing W/C_c ratio at advanced ages.

'Plateau' effect

This is noticeable in Venuat's (18) work but there is no obvious explanation. The effect is less marked with Pozz. 2 mixes which suggests that it could be a particle size or % ignition loss phenomenon, since the gradings and % ignition loss are significantly different although the materials are from the same source. (See Fig. 1 T. 4.3.2.C, G 4.3.2.)

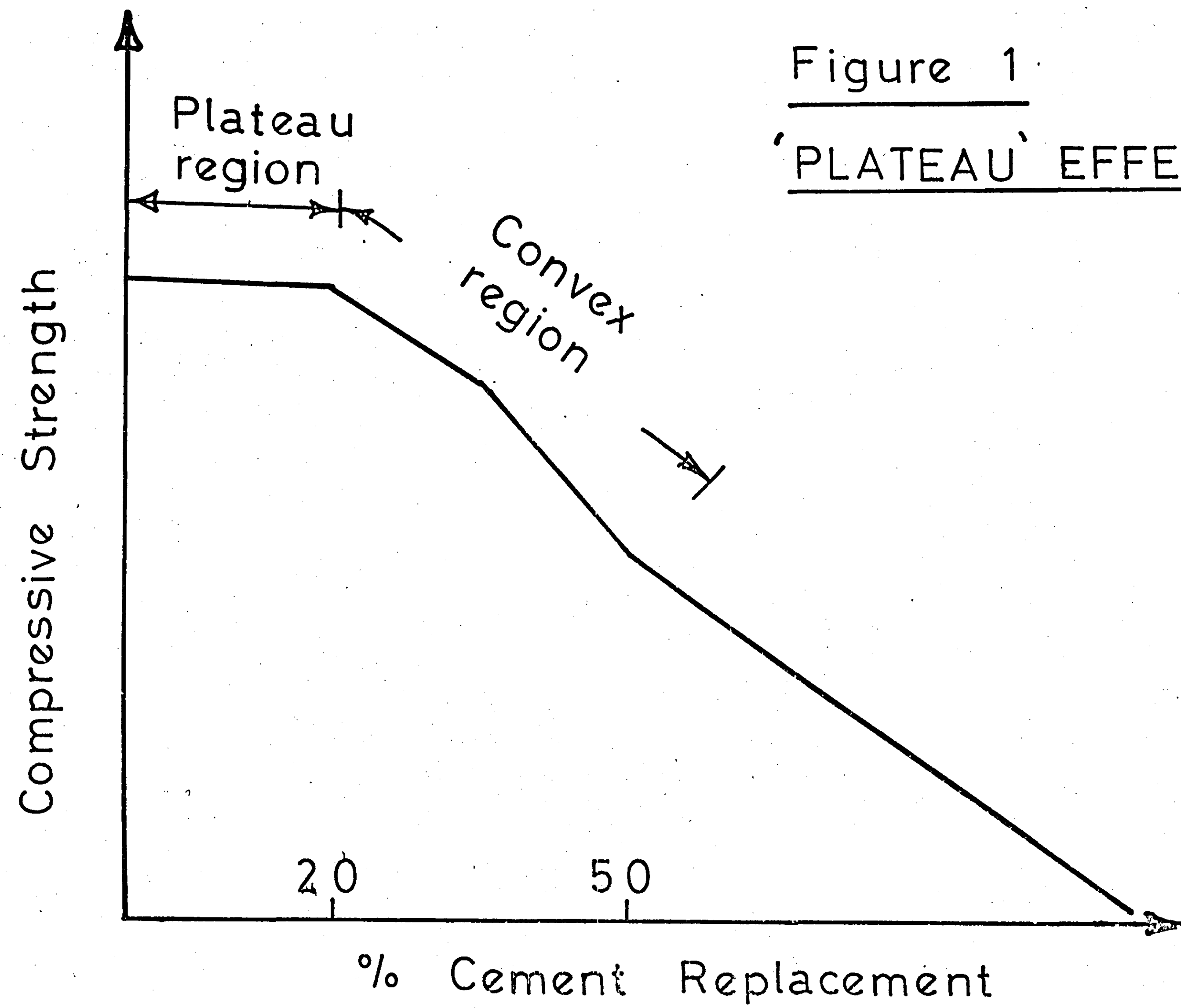


Figure 1

'PLATEAU' EFFECT

Increasing convexity

Increasing convexity, for increased ages was apparent in Venuat's (18) work and implies that for increasing % C.R. the maximum strength is achieved at later ages. This is probably due to pozzolanic activity between the free lime and p.f.a. which tends to be a long term phenomenon.

% loss in strength for different $^{W}/_{C_C}$ ratio

The different water demand of p.f.a. with respect to cement is likely to be apparent at low rather than high $^{W}/_{C_C}$ ratios and at advanced ages percentage differences owing to the influence of pozzolanic activity are likely to be reduced, therefore the author suggests that this difference in % loss in strength is probably a water demand phenomenon.

Pozzolan 1 and Pozzolan 2

In general, the compressive strength of Pozz. 1 mixes slightly exceeded that of the corresponding Pozz. 2 mixes. In addition, there was little evidence of pozzolanic activity at later ages (182 days) with Pozz. 2 in contradistinction with contemporary Pozz. 1 strengths. (see G. 8.3.2.1/2).

9.3.4 Compressive Strength v % Cement replacement at different % Fine Aggregate replacement (F.A.R.) (See G. 8.3.3.1. - 3.9)

9.3.4.1 General

Reference to G.8.3.3.1. - 3.9. shows that in general the Compressive Strength (C.S.) decreases with increasing % Cement Replacement (C.R.) at all W/C_c ratios and fine aggregate replacement (F.A.R.) levels.

The 'plateau' effect referred to in the previous section (9.3.3) is apparent for Pozz. 1 but not for Pozz. 2 - see G. 8.3.3.1.-3.9.

There is a tendency for Pozz. 2 F.A.R. curves to follow a narrow band irrespective of the % F.A.R. or W/C_c ratio. However, Pozz. 1 appears to be more sensitive to F.A.R. than Pozz. 2 evidenced by the larger 'bandwidths' of results.

The convexity of curves referred to previously is also apparent at advanced ages - see G. 8.3.3.1. - 9.

9.3.4.2 25% F.A.R. for Pozz. 1 at W/C_c = 0.50

This level of F.A.R. has a marked effect upon the compressive strength of concrete mixes for all % C.R. at all the ages considered. (See G. 8.3.3.2./5./8.)

The 28 day compressive strength is maintained within the 90% Control limits up to 35% C.R. but with a 50% C.R. the compressive strength falls off rapidly, see

9.3.4.3 Discussion

Two principal features emerge from above, namely:-

i) Pozzolan 2 appears less sensitive to F.A.R. than Pozzolan 1.

ii) An F.A.R. = 25% maintains control values of compressive strength over a large range of C.R. for Pozz. 1 mixes.

There are two principal differences between Pozz. 1 and Pozz. 2 namely the fineness of material (see Table T. 4.3.2.C & Graph G.4.3.2.) and the % loss on ignition (see Table 4.3.2.C)

The water demand as indicated by the standard consistency test (47) indicates that Pozz. 2 has a higher water demand than Pozz. 1. However, the standard consistency test being a single point test, does not discriminate between plasticity and interparticular friction, i.e. a material with high internal friction is likely to require a larger moisture content to initiate movement than one with low internal friction although the plasticity of the material may be low. In making the specimens for the standard consistency test the author observed that Pozz. 1 revealed a much higher degree of plasticity than Pozz. 2.

The author contends therefore that the behaviour of Pozz. 2 is closer to that of a fine aggregate than Pozz. 1 and is therefore likely to be less influential upon the mobility and available free water than Pozz. 1. The net effect is therefore a compound one influencing both the degree of compaction and the hydration rate both of which affect strength.

It may be noted that the workability, as measured by compacting factor, of mixes with Pozz. 1 F.A.R. are consistently higher than the corresponding Pozz. 2 mixes.

9.3.5 <u>28 day Compressive Strength versus W/C_c ratio at 0% Cement replacement and 0 - 35% Fine aggregate replacement (See G. 8.3.4.)</u>

9.3.5.1 <u>General Observations</u>

For clarity points have been omitted from graph G. 8.3 for details see Appendix IV. Compressive Strength decreases with increasing W/C_c ratio for all % F.A.R.s.

<u>W/C_c = 0.4</u>

The optimum F.A.R. for strength is 15% for Pozz. 1 and Pozz. 2, and in passing it is notable that it was not possible to manufacture mix P100/35/40, as this was too dry to compact.

<u>W/C_c = 0.5</u>

F.A.R. appears to have little effect upon strength except for P100/35/50 which displays a compressive strength approximately 20% above the corresponding 0 to 25% F.A.R. mixes.

$W/C_c = 0.6$

The variation in compressive strength of Pozz. 2 is erratic but F.A.R. = 5% and 35% appear to be the most favourable for strength development.

Pozz. 1 is a little less irregular and an F.A.R. of 25% yields the peak 28 day strength.

Sensitivity to water content

The sensitivity to change in water content is high, as much as 35 N/mm^2 between W/C_c = 0.40 and 0.60. This is equivalent to an average rate of change in strength of 0.55 N/mm^2 per kg of water compared with only 0.2 N/mm^2 per kg of cement at the same age. (See G. 8.3.4)

Range of strengths for given% F.A.R.

The minimum compressive strength ranges for Pozz. 1 corresponds to F.A.R. = 25% and that for Pozz. 2 to an F.A.R. = 35%.

9.3.5.2 Discussion

These results vindicate what has been suggested previously with respect to the relative water demands of Pozz. 1 and Pozz. 2 in that for a given W/C_c ratio a larger volume of Pozz. 2 can be incorporated as a replacement for fine aggregate than Pozz. 1. The higher water demand of Pozz. 1 results in a much lower workability at very high F.A.R. and hence poor compaction is achieved. Notwithstanding this however, it appears that at 25% F.A.R. with Pozz. 1 the concrete is much less sensitive to changes in water content (W/C_c ratio) as evidenced by a change of only 20 N/mm^2 corresponding to a W/C_c difference of 0.2. This yields a rate of change of only 0.3 N/mm^2 per kg. It must be added however that a considerable decrease in workability is incurred for W/C_c = 0.40 at this F.A.R. level. (See G. 8.2.1.1)

The minimum strength range for Pozz. 2 (F.A.R. = 35%) is only 15 N/mm^2 for W/C_c difference = 0.2 which is more favourable but without the maintenance of higher strengths throughout a large range of cement replacements which is achieved with Pozz. 1 at F.A.R. = 25% (See 8.3.4.). Workabilities of Pozz. 2 are also inferior to those of Pozz. 1 at their corresponding optimum ranges. (See G. 8.2.1.2.)

9.3.6 Relationship between Compressive Strength (Fc) and Indirect Tensile Strength (Ft)

(See Fig. 2 and G. 8.3.5.1./2.)

9.3.6.1 General Observations

The above relationship appears to be described by the following curvilinear functions for Control and General mixes.

T. 9.3.6.1	Regression curve		Coefficients of correlation	
Function Form	Control	General (All mixes)	Control	General (All mixes)
$Y = Ax^B$	Fc = 10.43 Ft 1.18	Fc = 7.86 Ft 1.37	0.984	0.959
$Y = Ae^{Bx}$	Fc = 6.60e Ft 0.53	Fc = 6.39e Ft 0.53	0.984	0.940

Summary observations from above are as follows;-

i) There is a high correlation between Compressive Strength and Indirect Tensile Strength with all functions.

ii) The 'power' law ($Y = Ax^B$) appears to be more representative of low strength concrete whereas the 'exponential' law ($Y = Ae^{Bx}$) is more representative of high strength concrete. (see Fig. 2)

iii) Compliance of results with the above functions appears to be independent of water, cement, fine aggregate, and pozzolana content.

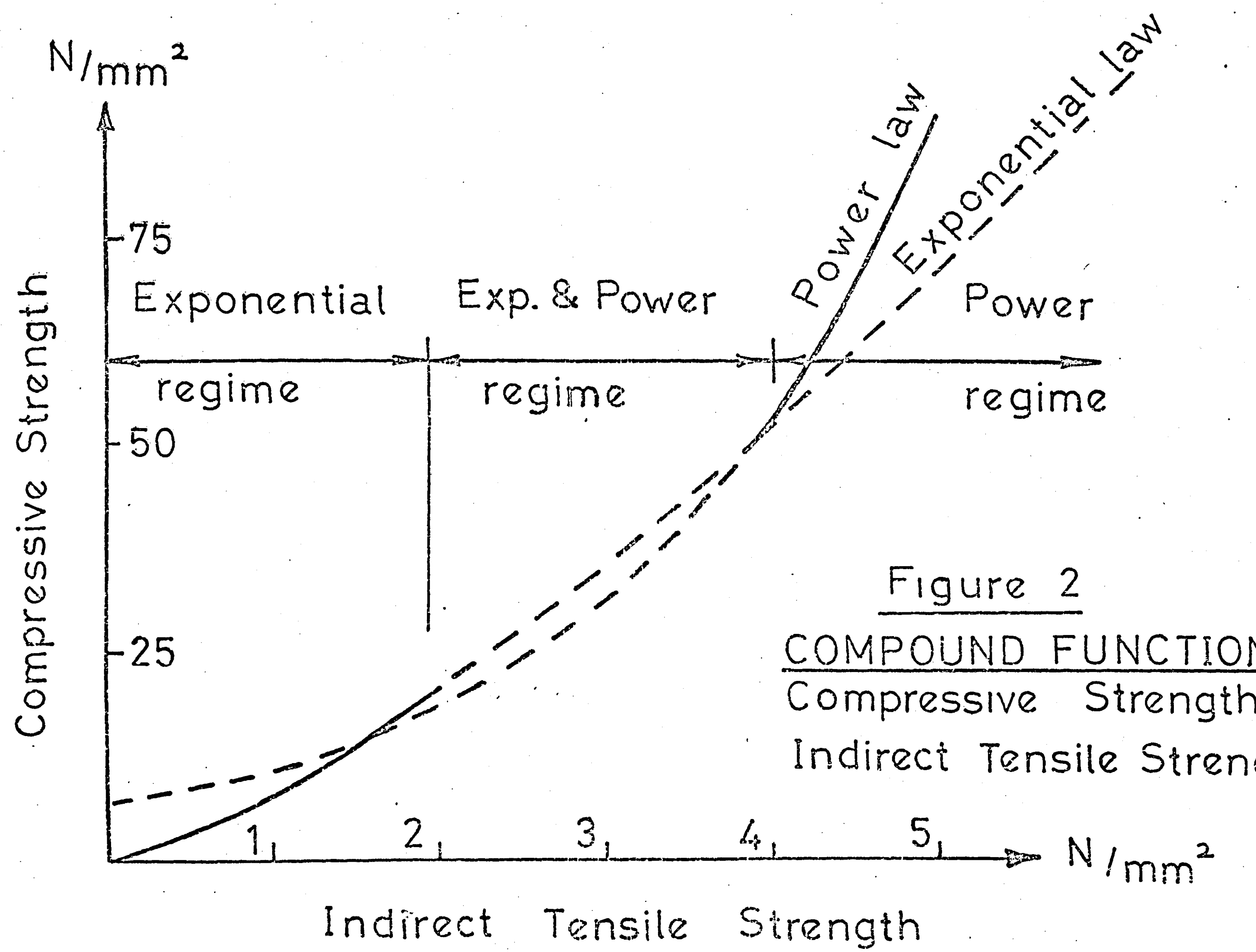


Figure 2

COMPOUND FUNCTION

Compressive Strength v. Indirect Tensile Strength

iv) The close proximity of the Control and General curves indicates that % Cement and % Fine aggregate replacement with Pozzolana has little significant influence upon the relationship between compressive strength and indirect tensile strength.

9.3.6.2 Discussion

9.3.6.2.A Functional relationships

Previous work (66) (67) (68) has indicated a curvilinear relationship between compressive strength and indirect tensile strength. However, most research indicates a power law relationship. Results are summarised as follows:-

T. 9.3.6.2A Comparison of results from authors of previous work

Name (Country)	Function	Details of test age
Akazawa (68) (Japan)	$Fc = 3.92\ Ft^{1.37}$	7 and 28 days
Carneiro-Barcellos (67) (Brazil)	$Fc = 4.35\ Ft^{1.36}$	7, 28, 84 days
Molhotra (66) (Canada)	$Fc = 0.100\ Ft^{1.77}$	28 days
The Author - 'Control'	$Fc = 10.43\ Ft^{1.18}$	1, 7, 14, 28, 91 days.
The Author - 'General'	$Fc = 7.86\ Ft^{1.37}$	1, 7, 14, 28, 91 days.

Agreement between Akazawa (68), Carneiro-Barcellos (67) and the author's power coefficients is good. However there is a wide disparity between the results of the author and those of Mulhotra (66). This could be accounted for by the very large range of $W/_C$ ratios (0.31 - 1.03) and aggregate cement ratios (2.69 - 9.69) used by Mulhotra. The range of $W/_C$ ratios used by the author were by comparison much smaller (0.30 - 0.70) as was the aggregate cement ratio range (4.91 - 5.69). The correlation coefficients for the results included all exceeded 0.90.

The author considered that the relationship between indirect tensile strength and compressive strength can be best described by a two part function namely a power law for Ft = 1.0 - 4.0 N/mm^2 and an exponential law for Ft = 2.0 - 5.0 N/mm^2. For concrete with Ft = 2.0 - 4.0 N/mm^2 a power or exponential law is applicable. It is most probable that this two-part function is due to a change in the fracture mechanism as the concrete strength (cement matrix/aggregate bond) changes with age, $W/_C$ ratio, cement content etc. At low strengths it was noted that the large majority of coarse aggregate particles displayed an aggregate/cement matrix bond failure i.e. the aggregate pulled out of the matrix whereas at high strengths the fracture plane had a greater tendency to go through the coarse aggregate particles. These were both noted after examining the broken halves of a split cylinder specimen. This change in fracture mechanism could occur to the cubes in the compressive strength test. However, if it does, it implies that the effects are disproportionate in the two testing methods. These fracture mechanisms were also noted by Hannant et al and Chapman (69) (70).

9.3.6.2 B <u>Effect of Constituents</u>

<u>Type and Proportions</u>

Water, cement, fine aggregate and pozzolana content all mutually influence the ratio of indirect tensile strength : compressive strength in their effect upon the strength of concrete however, none of them had any independent influence in this context. The effect of including Pozz. 1 or Pozz. 2 was also insignificant in this respect.

<u>Grading</u>

It has been suggested (71) that increasing the coarseness of material in concrete results in an increase in the indirect tensile strength : compressive strength ratio. Although the gradings of the interchanged materials, cement, fine aggregate, Pozz. 1 and Pozz. 2 were markedly different it did not appear to have a significant effect.

Previous research has shown the most significant factor influencing the relationship between compressive strength and indirect tensile strength to be the relative size and the type of aggregate. (69) (70) (71) Although the specimen size and aggregate type remained the same throughout, the effect of replacing part of the fine aggregate with pozzolana appeared to have little influence.

Effects of Age

Age affected both the indirect tensile and compressive strengths and hence their ratio however all results conformed to one or other of the functions described previously.

9.3.7 Relationship between Compressive Strength (Fc) and Ultra-sonic Pulse Velocity (V) (See G. 8.3.5.3)

9.3.7.1 General Observations

In accordance with previous methods and practice (43) (72) the author plotted these variables in the form

$$\ln Fc = \ln A + BV \quad (43)\ *$$

giving a linear relationship if plotted on semi-log paper as follows:-

T. 9.3.7.1	Regression Curve		Coefficient of correlation	
Function Form	Control	General (All mixes)	Control	General (All mixes)
$Y = Ae^{Bx}$	$Fc = 0.0107e^{1.78V}$	$Fc = 0.0144e^{2.21V}$	0.969	0.873

* A and B are constants.

Initial observations can be summarised as follows:-

i) 'Control' and 'General' results appear to conform to the relationship postulated.

ii) Scatter of results increases dramatically below V = 4.0 km/sec., Fc = 10 N/mm^2.

iii) 'Control' results display higher correlation than 'General' results.

iv) There appears to be a notable difference between the curves posulated for 'Control' and 'General' results.

9.3.7.2 Discussion

The expression for the ultra-sonic pulse velocity (V) of a pulse through concrete is given by

$$V = \sqrt{\frac{E_D}{\rho} \frac{(1 - \nu)}{(1 + \nu)(1 - 2\nu)}} \qquad (33)$$

and

$$\frac{1}{E_D} = \frac{Va}{E_A} + \frac{(1 - Va)}{E_M} \qquad (73)$$

where

V = ultra-sonic pulse velocity of a wave propagated through concrete.

E_D = dynamic modulus of elasticity (concrete).

E_A = dynamic modulus of elasticity (aggregate).

E_M = dynamic modulus of elasticity (mortar).

Va = volume fraction of aggregate.

ν = Poisson's ratio.

ρ = relative density of concrete.

Simmons (73) showed that 'ν' was largely independent of mix proportions and aggregate grading for a constant workability using aggregate from the same source. and further that 'ν' decreases with increase in age of concrete to an approximately constant value.

Newman (74) suggests that increasing the volume fraction of coarse aggregate imposes added restraint within the matrix thus reducing Poisson's ratio (ν).

For the mixes produced by the author the variation in the volume fraction of fine and coarse aggregate was relatively small (0.74 - 0.61); assuming Pozz. 1 and 2 as part of the mortar. This corresponds to a change in 'ν' of 0.02 according to the results of Anson quoted by Newman (74).

Neville (75) states that the relationship between modulus of elasticity (E_D) and strength depends upon the mix proportions and the age of the specimen (since aggregate generally has a higher modulus than the cement paste). This suggests a limiting value of E_D for concrete (author).

Simmons (73) showed that in the lower range E_D was proportional to E_S (Static modulus of elasticity for concrete). However, the large scatter for large values of moduli could be due to experimental discrepancies associated with concrete since E_D and E_S for metals are shown by Simmons to be in close agreement.

From the above the author postulates the following regarding his own results; although it must be emphasised that further investigation outside the scope of this thesis would be necessary to establish their verity.

i) As concrete age/strength increases the value of pulse velocity (V) becomes independent of Poisson's ratio (ν) as the term (73)

$$\frac{1 - \nu}{(1 + \nu)\ (1 - 2\nu)} \longrightarrow \text{constant value}$$

ii) Assuming the above to be correct then

$$V \propto \sqrt{\frac{E_D}{\rho}} \quad \text{for higher strength concretes.}$$

iii) The higher strength concretes are largely constituted by those of later age and low cement replacement therefore the variation in Va and ρ hence pulse velocity (V) tends to be lower for high strength concretes.

iv) The converse tends to be the case at early ages exaggerated by the influence of Poisson's ratio (ν) for immature concretes (see i)) hence the increased scatter of results as strength decreases.

9.3.8 Relationship between Indirect Tensile Strength (Ft) and Ultra-sonic Pulse Velocity (V) (G. 8.3.5.4.)

9.3.8.1 General Observations

The author could find little previous work involving relationships between 'Ft' and 'V' however a function of the form $Y = Ae^{Bx}$ has been used to relate modulus of rupture with 'V'. (43)

The author therefore decided to employ a similar function to that used to relate Fc to V. The results are included below.

T. 9.3.8.1	Regression Curve		Coefficient of correlation	
Function Form	Control	General	Control	General (All mixes)
$Y = Ae^{Bx}$	$Ft = 0.0035e^{1.47V}$	$Ft = 0.0025e^{1.55V}$	0.968	0.841

Initial observations are summarised below:-

i) 'Control' and 'General' results appear to conform with the relationships postulated.

ii) Scatter of results tends to increase below V = 4.0 km/sec., Ft = 2.0 N/mm^2.

iii) 'Control' results display a higher degree of correlation than 'General' results.

iv) The curves relating 'Control' and 'General' results are very similar.

9.3.8.2 Discussion

The factors influencing the relationship between compressive strength (Fc) and Ultra-sonic pulse velocity (V) have been discussed previously. Similar factors affect the relationship between Ft and V however from these results it appears that at least one of these is less dominant than in the previous case since the 'Control' and 'General' functions relating Ft with V almost coincide.

The author suggests that the indirect tensile strength is more dependent upon the coarse aggregate volume fraction than is the compressive strength (see earlier discussion 9.3.6.2A/B.) The coarse aggregate fraction remained approximately constant throughout the range of mixes tested. Therefore the influences of age/strength and Poisson's ratio, only, are likely to predominate in the relationship of Ft versus V.

9.3.9 Relationships between mix constituents/ proportions and mix parameters using correlation coefficients. (See T. 8.3.6.1 - 6.6)

9.3.9.1 General Observations

These were investigated by compiling a correlation matrix including cement, pozzolan and fine aggregate as the independent variables and compressive, indirect tensile strengths, ultra-sonic pulse velocity and cube weight as the dependent variables. Matrices were obtained at three different ages 7, 28 and 91 days and three W/C_c ratios 0.40, 0.50 and 0.60 for Pozzolan 1 and Pozzolan 2 mixes.

The purpose for which these tables could be used was threefold, namely:-

i) The assessment of the influence of pozzolanic activity upon strength by comparing correlation coefficients at different ages.

ii) A comparison of the correlation coefficients between different test parameters.

iii) The assessment of the relative influence upon strength at different ages of cement, pozzolan and fine aggregate content.

9.3.9.2 Correlation between Compressive Strength and Pozzolan content

The correlation coefficient tables indicate generally that pozzolan content correlates negatively with compressive strength although this negative correlation only reaches significant values at low water contents and with the use of Pozz. 2 but not with Pozz. 1.

There is little evidence to suggest that pozzolanic activity is taking place with either Pozz. 1 or Pozz. 2 during the first 91 days. The largest positive change in correlation coefficient is from -0.39 to -0.05 with Pozz. 1 at $W/_{C_c} = 0.50$.

9.3.9.3 Correlation between Compressive Strength and Cement content

There is strong positive correlation at all ages and $W/_{C_c}$ ratios, the lowest value being 0.81, thus implying that cement content has a significant effect upon strength, as expected.

9.3.9.4 Correlation between Compressive Strength and Fine Aggregate content

The correlation is generally negative and weak tending to become increasingly positive as W/C_c ratio decreases.

9.3.9.5 Correlation between Cube Weight and Pozzolan content

This reveals an exclusively negative correlation which becomes stronger with decrease in W/C_c ratio.

9.3.9.6 Correlation between Compressive Strength/ Indirect Tensile Strength/Ultra-sonic Pulse Velocity

Correlations between the above confirm the findings of sub-sections 9.3.6.-8. and are summarised briefly below.

9.3.9.7 Summary observations

i) Compressive Strength/Indirect Tensile Strength:-

Coefficients are high at all ages and W/C_c ratios. Correlation is positive.

ii) Compressive Strength/Ultra-sonic Pulse Velocity:-

Coefficients are high at all ages and W/C_c ratios. Correlation is positive.

iii) Indirect Tensile Strength/Ultra-sonic Pulse Velocity;-

Coefficients are high and largely independent of age and W/C_c ratio. Correlation is positive.

9.3.9.8 Discussion

Pozzolanic activity and water demand

It is clear from these results that the strength gain at later ages due to pozzolanic activity is relatively small within the first 91 days. Most of the strength gain attributable to inclusion of pozzolan is probably as the result of its use as a fine aggregate replacement which is indirectly evident from the increasing negative tendency of the correlation coefficients between strength and fine aggregate content as W/C_c increases. The water demand of mixes with increasing F.A.R. tends to increase. Increased strength resulting from this becomes more apparent at higher W/C_c ratios owing to the effective reductions of free water in the mix.

Relative density and cube weight

The relative densities of Pozz. 1 and Pozz. 2 are considerably less than the fine aggregate and cement which they replace hence the negative correlation between pozzolan content and cube weight. The relationship between cube weight and strength tends to be capricious as a result of the above.

Strength correlations

These have been described in detail previously however it is clear that correlation between compressive strength/ultra-sonic pulse velocity/indirect tensile strength are positively strongly correlated.

9.4 Durability Tests (see Appendix V and 8.4)

9.4.1 Introduction

Previous reference has been made to the method used to assess durability. Tests were carried out by determining the % weight loss of 100mm concrete cubes, together with ultra-sonic pulse velocities across and along 100 x 100 x 500mm concrete prisms after they had been immersed in a 3.5% (anhydrous) Magnesium Sulphate ($Mg\ SO_4$) solution for an average period of 2 years. The author wishes to add that the following test results are by no means conclusive and specimens remain in the $Mg\ SO_4$ solution pending further tests.

The author considered that at this stage i.e. after 2 years, changes in the Ultrasonic pulse velocity were not sufficient to indicate any significant deterioration of the specimens; probably because most specimens were sufficiently impermeable to prevent attack throughout the whole of the specimen.

In view of the short period of immersion (the average was 12 months) the variation in % weight loss was in some cases considerable. The average % weight loss of the three cubes representing each mix was compared with that of the mean - 1.64 x standard deviation (control) and the mean - 1.64 x standard deviation (general). The 'general' represents the total population of the mixes tested. % weight losses exceeding the former (control) figure are ringed in 'Yellow' and those exceeding the latter figure (general) are ringed in 'Red'. Full results are included in Appendix V. For brevity, however, the most salient points have been extracted from the results and put in tabular form below.

The author wishes to add that although mixes ringed in 'Red' are considered to have suffered a greater degree of Mg SO_4 attack than those ringed in 'Yellow' it must be emphasised that these results are only comparative and that no attempt is being made to extrapolate these results to a 'real' engineering situation, when different Mg SO_4 concentration and environmental conditions might cause the relative behaviour of specimens to be much different from that indicated from these results.

T. 9.4.2 A 'Control' and 'General' Limits and Designation

Parameter / Type	Mean % weight change	Standard deviation % weight change	90% lower limit = Mean - 1.64 x Std. Dev.	Designation of 90% lower limit
Control	+ 0.760	0.36	+ 0.17	Yellow
General	+ 0.060	1.32	- 2.11	Red

T. 9.4.2 B No. of mixes exceeding % weight loss limits

W/C ratio	Pozzolan 1		Pozzolan 2		Totals	
	Yellow & Red	Red	Yellow & Red	Red	Yellow & Red	Red
0.40	10 (14)	1 (14)	10 (16)	1 (16)	20 (30)	2 (30)
0.50	6 (21)	1 (21)	5 (20)	0 (20)	11 (41)	1 (41)
0.60	6 (14)	2 (14)	6 (15)	0 (15)	12 (29)	2 (29)
Totals	22 (49)	4 (49)	21 (51)	1 (51)	43 (100)	5 (100)

Figures in brackets indicate total number of mixes tested in that group.

T. 9.4.2 C <u>% of mixes exceeding % weight loss limits</u>

$W/_{C_c}$ ratio	Pozzolan 1		Pozzolan 2		Totals	
	Yellow & Red	Red	Yellow & Red	Red	Yellow & Red	Red
0.40	71	7	63	6	67	7
0.50	29	5	25	0	27	2
0.60	43	14	40	0	41	7
Totals	45	8	41	2	43	5

9.4.2 <u>General observations</u>

Results have been tabulated above to give an indication of both the number and % of mixes (expressed as % of mixes in that particular group) whose % weight loss exceeds the 'Yellow' and 'Red' limits in T. 9.4.2.B in relation to their $W/_{C_c}$ ratio and the type of Pozzolan which they incorporate.

The results indicate that a substantial proportion of the pozzolan mixes tested had inferior resistance to $Mg\ SO_4$ attack compared with the 'control' although one of the O.P.C. base mixes (00/00/60) exceeded the 'Yellow' limit.

9.4.2.1 Influence of W/C_c ratio

It appears from T. 9.4.2.C that the mixes with a W/C_c ratio = 0.50 are more resistant to Mg SO_4 attack followed by W/C_c = 0.60 and 0.40 in that order.

9.4.2.2 Influence of Pozzolan type

Pozz. 1 appears to be more vulnerable to severe attack (% exceeding 'Red' limit) than Pozz. 2 at all W/C_c ratios. However, its vulnerability to mild attack (% exceeding 'Yellow' limit) appears to be comparable to that of Pozz. 2 except at W/C_c = 0.50 where its resistance is inferior to that of Pozz. 2.

9.4.3 Discussion

Influence of W/C_c ratio

High and low water contents both result in a relatively high void or pore content. The former largely because of insufficient compaction (increase in void space) and the latter because of diluted paste (increase in pore space). The consequent increase in permeability enables easy access by salts in solution leading to disintegration of specimen at greater depth as the Mg SO_4 reacts with the tricalcium aluminate (C_3A) and calcium silicate hydrates (76). Reference to porosity and its influence upon vulnerability to sulphate attack suggested by Venuat has been mentioned previously (see Chapter 2.0).

Influence of Pozzolan type

As mentioned above, $Mg\ SO_4$ attacks both calcium aluminate and calcium silicate hydrates therefore replacing O.P.C. with pozzolan thereby reducing the proportion of C_3A has less influence upon the resistance of concrete to $Mg\ SO_4$ attack than it does with other sulphates. The chief advantage of using pozzolanas is probably an indirect one in that continuing pozzolanic activity progressively fills the pores in the concrete thus reducing the permeation rate of the aggressive solution. (76)

The comparatively superior resistance to $Mg\ SO_4$ attack of Pozz. 2 over Pozz. 1 is possibly attributable to two mutually interacting factors namely:-

i) The difference in % ignition loss of Pozz. 1 and Pozz. 2.

ii) The difference in their relative water demand.

i) Pozz. 2 has a higher ignition loss than Pozz. 1 and therefore the proportion of potentially reactive material is less in the former case than the latter, hence lower disruptive stresses are likely due to sulphate reaction. However, this % difference in ignition loss is only 2% (see T. 4.3.2.C)

ii) At low water contents and high F.A.R. Pozz. 1 mixes were more difficult to compact than Pozz. 2 at the same level of replacement (see G. 8.2.1.1.). This also applies to a limited extent for medium water contents ($^{W}/_{C_c}$ = 0.50) (see G. 8.2.1.2)

Such mixes would tend to be more permeable therefore more vulnerable to attack (see Appendix V and compare mixes P100/35/50 with P200/35/50).

Whatever the cause of this apparant superiority of Pozz. 2 this aspect is one which requires further investigation.

CHAPTER 10

CONCLUSIONS AND SUGGESTIONS FOR FURTHER WORK

10.0 Conclusions and Suggestions for Further Work

10.1 Introduction

The author will begin firstly with a summary of the general conclusions reached in the previous sections of text following which the economics of cement and fine aggregate replacement in terms of the workability, strength and durability requirements are dealt with. An attempt is subsequently made to choose a mix which the author considers to be behaviourally the closest to the control mix from workability, strength, durability and economic considerations.

Finally the main findings of the research are given, their implications discussed and recommendations for future development and work are given.

10.2 The Effect of Pozzolan 1 and 2 upon Concrete Properties

10.2.1 General observations

The behaviour of concrete mixes incorporating Pozzolan is generally dependent upon both the type of pozzolan (Pozz. 1 or Pozz. 2) and the proportion of cement and fine aggregate replacement. Incorporation of Pozz. 1 is generally more favourable from workability and strength considerations but the converse is the case regarding durability.

10.2.2 <u>Workability</u> (see G.8.2.11 - 1.3 and 9.2.2)

i) For low and medium water contents (W/C_c, i.e. constant water volume = 0.40 and 0.50) replacement of cement with Pozz. 1 generally improves workability.

ii) At low and medium water contents fine aggregate replacement (F.A.R) with Pozz. 1 and Pozz. 2 results in decrease in workability.

iii) The effect of i) is enhanced for medium water content and F.A.R = 15% and 25%.

iv) For high F.A.R. 15, 25 and 35% and 10 - 35% cement replacement the workability of Pozz. 1 mixes exceeds that of corresponding Pozz. 2 mixes.

v) For high water contents (W/C_c = 0.6) cement replacement enhances workability slightly above control values.

10.2.3 <u>Strength</u> (see G. 8.3.2, G. 8.3.3, G. 8.3.4 and 9.3.3 - 9.3.5)

i) Increasing % cement replacement with Pozz. 1 and Pozz. 2 results in decrease in strength at all water contents.

ii) The Compressive Strength versus % cement replacement (C.R.) curves are marked by a strength 'plateau' between C.R. = 10 - 20% with Pozz. 1 mixes.

iii) Compressive Strength versus % cement replacement curves tend to increase in convexity at later ages implying a later development of peak strength for increasing % C.R.

iv) Increasing F.A.R. with Pozz. 1 results in an increase in strength at higher levels of replacement and medium water contents (W/C_c = 0.50).

v) Pozz. 2 is relatively insensitive to F.A.R. at medium and high water contents (W/C_c = 0.50 and 0.60)

vi) Sensitivity of strength to change in water content is minimised for F.A.R. = 25% and 35% for Pozz. 1 and Pozz. 2 respectively for W/C_c between 0.40 and 0.60.

vii) Strengths within the 90% control limits can be maintained with cement replacement up to 35% with F.A.R. = 25%.

10.2.4 Durability (see T. 9.4.2 A - C)

i) Low and high water contents ($^W/_{C_c}$ = 0.40 and 0.60) adversely affect resistance of Pozz. 1 and 2 concretes resistance to $MgSO_4$ attack.

ii) The resistance of Pozz. 2 concretes to $MgSO_4$ attack is superior to that of Pozz. 1 concretes especially at medium water content ($^W/_{C_c}$ = 0.50)

10.3 Relationships between Testing Methods

10.3.1 Workability (see G. 8.2.2, T. 8.2.3. and 9.2.3/4)

i) Slump and VeBe results correlate well with Compacting Factor but there is large scatter especially for low workability mixes.

ii) The 2 point workability test correlates reasonably with Compacting Factor but not with Slump and VeBe tests.

10.3.2 Strength (see G. 8.3.5., T. 8.3.6. and 9.3.6 - 9.3.8)

i) A bi-functional (power and exponential laws) relationship exists between Indirect Tensile Strength and Compressive Strength test results. These relationships appear to be little influenced by mix type, proportions, etc., and are almost identical for control and mixes containing pozzolan.

ii) Ultra-sonic pulse velocity appears to be related to compressive strength by an exponential relationship. The nature of this relationship does appear to be influenced by mix type and proportions.

iii) Ultra-sonic pulse velocity appears to be related to indirect tensile strength by an exponential relationship. In contrast with ii) the 'control' and 'general' exponential functions are very similar seeming to indicate that this relationship is less dependent upon mix variables.

10.4 Correlation between mix proportions and parameters (see T. 8. 3.6 and 9.3.9)

10.4.1 Pozzolan content and strength

i) There is little evidence of pozzolanic activity contributing to strength during the first 91 days.

ii) By inference from the correlation between fine aggregate content and strength, pozzolan content influences strength by its effect upon the water demand of the mix.

10.4.2 Pozzolan content and cube weight

i) Cube weight and therefore concrete density is considerably affected by pozzolan content in an inverse manner, i.e. as pozzolan percentage increases concrete density decreases owing to effect of relative density.

10.4.3 Strength correlations

i) Correlations between all strength tests confirm the findings of 10.3.2, coefficients in the majority of cases exceeding 0.90.

10.5 Economy of mix design

10.5.1 Economic variables

The criteria of cost and performance discussed in the earlier parts of this text can now be evaluated and discussed with the benefit of available data.

The principal factor to emerge from these results is that Pozz. 1 maintains workability and strength properties closer to that of the 'control' than Pozz 2 for the majority of mixes tested. However, the performance benefits are offset by the increased cost of Pozz 1 incurred through selecting it from the raw p.f.a. (Pozz 2). The question posed therefore is whether the increased processing cost is outweighed by the performance benefits i.e. cost/benefit considerations.

One of the major disadvantages with Pozz. 2 is its inherent variability which is related to power station output conditions and source of coal. The selection process reduces this variability considerably and a more consistent product tends to be produced.

With these factors in mind the author has surveyed the results and chosen a mix whose performance in terms of workability, strength and durability most closely matches that of control at all ages.

10.5.2 Comparison of 'Control' with 'Ideal' pozzolan mix *

The mix chosen was P 135/25/50. It will be noted that this mix incorporates both cement and fine aggregate replacement with Pozz. 1. The former tends to decrease whilst the latter tends to increase the cost of concrete produced, however, in this case a more economical mix than control has been chosen.

* see G.8.2.1.2.G. 8.3.3.5., Appendix V page and T. 5.6.3.

Details both of the 'control' (00/00/50) and the 'ideal' (P 135/25/50) replacement are included in tabular form below.

Table 10.5.2A 'Control' and 'Ideal' concrete mix properties - Workability, Strength, Durability and Cost.

Concrete properties	'Control' (00/00/50)	'Ideal' (P 135/25/50)	Units
Compacting Factor	0.905	0.870	-
7 day Compressive Strength	37	31	N/mm^2
28 day Compressive Strength	52	47	N/mm^2
91 day Compressive Strength	60	63	N/mm^2
% Weight change in $MgSO_4$	+ 0.76	+ 0.54	%
Cost/m^3 * (1974)	5 - 75	5 - 60	£

* These figures should be multiplied by 1.07 to allow for yield. (See Table 5.6.4)

Table 10.5.2B <u>'Control' and 'Ideal' concrete mix properties - mix proportions and ratios</u>

Mix proportions and properties	'Control' (00/00/50)	'Ideal' (P 135/25/50)	Units
Water content (w) *	160	160	kg
Cement content (c) *	320	208	kg
Pozzolan 1 content (P) *	-	208	kg
Fine aggregate content *	630	470	kg
Coarse aggregate content*	1170	1170	kg
W/C_c ratio	0.50	0.50	-
W/C ratio	0.50	0.77	-
$W/(C + P)$	-	0.38	-
C/P ratio	-	1.0	-
C/Total Aggregate ratio	0.18	0.13	-
C + P/Total Agg. ratio	-	0.25	-
Fine Agg./Coarse Agg. ratio	0.54	0.40	-
Theoretically fully compacted density	2430	2365	kg/m^3

* These figures should be multiplied by 1.07 to allow for yield. (See Table 5.6.4)

The author wishes to comment only briefly regarding the comparative properties of mix 'Ideal' (P 135/25/50) and 'Control' (00/00/50).

Firstly, the chosen Pozz. 1 mix does not necessarily represent the ideal control substitute but was the mix which compared most favourably with 'control' out of those investigated.

Secondly, two important factors have emerged namely

a) the relatively high Pozz. 1/cement ratio of P 135/25/50, and

b) the low relative density of P 135/25/50 with respect to 00/00/50. (T. 10.5.2C)

Regarding a), Goodridge and Jackson (15) albeit using a different replacement technique found that the optimum p.f.a./cement ratio by weight = 0.60. The author's 'Ideal' mix has a Pozz. 1 (p.f.a.)/cement ratio of 1.0.

With respect to b) the reduction in relative density of concrete by incorporating pozzolan in concrete could certainly lead to energy savings in the vertical transportation of concrete and also construction savings by the reduction of dead loads owing to higher specific strengths. These may appear minor points but are nevertheless important in these days of slender profit margins.

Finally, the author wishes to point out that the cost-benefit of mix P 135/25/50 over that of 00/00/50 has since been enhanced slightly by a relatively large increase in the cement/Pozz. 1 price ratio compared with the Pozz. 1/ fine aggregate price ratio during the past 2 years.

Details of comparative costs as at June 1974 and June 1976 are given in Tables 10.5.2 C - E below. Of particular interest is the 3.3% saving over the 'control' in June 1974 compared with that of 6.5% in June 1976 an increase of 3.2% in favour of the Pozzolan 1 'Ideal' mix.

Table 10.5.2C * Unit Constituent weights and costs

	Weight (kg/m^3)		Cost £/tonne	
Constituent	Control	Ideal	June 1974	June 1976
Water	170	170	0	0
Cement	340	222	9 - 50	18 - 00
Pozzolan 1	-	222	5 - 50	8 - 00
Fine Aggregate	670	500	1 - 50	2 - 00
Coarse Aggregate	1250	1250	1 - 50	2 - 00
Total	2430	2364	-	-

* Figures adjusted for yield.

Table 10.5.2D * <u>Actual costs/m^3 of 'Control' and 'Ideal' mixes</u>

	Actual cost £/m^3 at June 1974		Actual cost £/m^3 at June 1976	
Constituent	Control	Ideal	Control	Ideal
Water	0	0	0	0
Cement	3 - 25	2 - 10	6 - 10	4 - 00
Pozzolan 1	-	1 - 20	-	1 - 80
Fine Aggregate	1 - 00	0 - 75	1 - 35	1 - 00
Coarse Aggregate	1 - 85	1 - 85	2 - 50	2 - 50
Total	6 - 10	5 - 90	9 - 95	9 - 30

Table 10.5.2E * <u>Comparative costs of 'Control' and 'Ideal' mixes</u>

	Difference between cost of Control & Ideal (June 1974)		Difference between cost of Control & Ideal (June 1976)	
Constituent	Actual £/m^3	% Control	Actual £/m^3	% Control
Water	0	-	0	-
Cement	+1 - 15	-	+2 - 10	-
Pozzolan 1	-1 - 20	-	-1 - 80	-
Fine Aggregate	+0 - 25	-	+0 - 35	-
Coarse Aggregate	0	-	0	-
Total	+0 - 20	3.3	+0 - 65	6.5

* Figures adjusted for yield.

10.6 Principal findings

The principal findings discussed in preceding parts of the text are summarised below. These will be followed by a concluding discussion and suggestions for further work.

i) Pozz. 1 and Pozz. 2 are significantly different both with respect to their physical and chemical content. (See Graph 4.3.2 and Table 4.3.2C)

ii) The workability and strength properties of concrete incorporating Pozzolan 1 are significantly enhanced compared with that of concrete incorporating Pozzolan 2. (see G. 8.2.1. and G. 8.3.2.)

iii) Pozzolan 2 concretes appear to be less susceptible to $MgSO_4$ attack than Pozzolan 1 concretes. (see T. 9.4.2.A - C)

iv) High fine aggregate replacements with Pozzolan 1 or 2 can reduce the variation in concrete strength with changing water content. (see G. 8.3.4.)

v) Cement replacements of 20% with Pozzolan 1 can be tolerated without substantial loss in strength compared with that of an O.P.C. control mix especially at ages greater than 91 days. (see G. 8.3.2.)

vi) Pozzolanic activity does not appear to have a significant effect upon concrete strength during the initial 91 days. (see T. 8.3.4.)

vii) The optimal mix from considerations of workability, strength, durability and economy compared with that of control was mix No. P 135/25/50. (see 10.5.2.)

viii) Relationships between different workability tests displayed high correlations but high scatter especially for decrease in workability.

ix) Relationships between different strength tests displayed high positive correlation at all strength levels.

x) Compressive Strength and Indirect Tensile Strength appear to be related by a bi-functional relationship which appears to be independent of the nature or degree of cement or fine aggregate replacement.

10.7 Concluding discussion

The principal object of this research was to investigate the effects of p.f.a. benefication and its influence upon the behaviour of concrete incorporating selected (Pozz. 1) and unselected (Pozz. 2) p.f.a. The author established that these materials were physically and to a lesser extent, chemically different and subsequently that these differences appear to have been reflected in the performance of concrete under test. Previous work (25) (26) has indicated the importance of the fineness of the p.f.a., indicated by the % passing No. 325 A.S.T.M. sieve and the % loss on ignition. These findings appear to have been vindicated by the author although for reasons referred to earlier he feels that in this case the fineness or grading of the material has been the most important factor.

Two novel findings have emerged in the author's view and these are:-

a) The large % fine aggregate replacement necessary to achieve near control strengths, and

b) The strength gain previously attributed to pozzolanic activity in some concretes is probably due to some other factor such as change in water demand of mix.

The economics of incorporating p.f.a. in concrete depends upon the relative price of constituents and the effect upon quality control of including a fifth material.

However, at the fine aggregate replacement level suggested by the author (25%) for the 'ideal' or 'optimal' mix, the rate of change in strength with changing water content is much reduced (Graph 8.3.4). The author feels that in industry the water content control is often neglected to the detriment of concrete especially considering its effect upon strength when compared with cement. In view of this any ingredient which reduces the strength sensitivity of concrete in this respect assists in producing a more uniform and consistent product.

The measurement of workability is a perennial problem with researchers. The author has chosen the compacting factor as the primary test because it is less operator sensitive than either the Slump or VeBe and tended to produce less variable results.

Results from the 2 point workability test were disappointing but the author feels that this was probably attributable to its high sensitivity to small variations in quality of materials compared with the British Standard tests. However, there remains an urgent need for the development of a more fundamentally based workability test. It was largely the absence of such a test which prompted the author to approach his mix programme from a 'grid' rather than a constant workability aspect as many previous researchers have done. (10) (15)

10.8 Suggestions for further research and development

10.8.1 Research

Throughout this research programme the author felt that there were certain shortcomings in both the knowledge of pozzolanic activity and the testing methods used to test the manufactured concrete and would like to see future research in the following fields.

i) Investigations into the fundamental nature of pozzolanic activity and its engineering implications similar to that done by Terrier and Moreau (24) in France.

ii) Development of more fundamentally based workability tests for fresh concrete perhaps along the lines of the 2 point test using different shear rates which relate to the methods of transportation and placing of concrete.

iii) Increasing work upon correlations between test methods used on pozzolanic and other concretes both in the field and laboratory.

10.8.2 Development

i) Increasing government effort to sponsor the implementation of a total ash utilisation concept as suggested by Sterling (28).

This would not only reduce costs but also utilise the material wasted as in the Pozzolan 1 selection process which approaches 30%. (77)

ii) Increased use of low cost transport e.g. rail and canal to reduce unit costs of p.f.a. Most power stations are rail or canal connected.

iii) Incentives to the cement industry to utilise p.f.a. in the production of p.f.a./O.P.C. blended cements as in France. (4)

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A P P E N D I X I

MIX PROPERTIES - PROPORTIONS

(Based on Table 50
CP 110)

N.B. To obtain quantities (kg) required to produce $1m^3$ of compacted concrete, multiply nominal quantities (kg) by appropriate Yield Factor.

MIX PROPERTIES - PROPORTIONS

P1/ /40

NO.	MIX CODE	WATER kg.	CEMENT kg.	POZZOLAN kg.	F.A. kg.	C.A. kg.	YIELD FACTOR
1	00/00/40	128	320	--	627	1173	1.104
18	P100/05/40	128	320	26	596	1173	1.104
13	P100/15/40	128	320	76	533	1173	1.104
6	P100/25/40	128	320	129	470	1173	1.104
--	P100/35/40	--	--	--	--	--	--
28	P110/00/40	128	288	23	627	1173	1.104
29	P110/05/40	128	288	48	596	1173	1.104
--	P110/15/40	--	--	--	--	--	--
--	P110/25/40	--	--	--	--	--	--
--	P110/35/40	--	--	--	--	--	--
41	P120/00/40	128	256	45	627	1173	1.104
42	P120/05/40	128	256	71	596	1173	1.104
85	P120/15/40	128	256	122	533	1173	1.104
--	P120/25/40	--	--	--	--	--	--
--	P120/35/40	--	--	--	--	--	--
66	P135/00/40	128	208	79	627	1173	1.104
75	P135/05/40	128	208	105	596	1173	1.104
91	P135/15/40	128	208	156	533	1173	1.104
--	P135/25/40	--	--	--	--	--	--
--	P135/35/40	--	--	--	--	--	--
56	P150/00/40	128	160	113	627	1173	1.104
--	P150/05/40	--	--	--	--	--	--
97	P150/15/40	128	160	190	533	1173	1.104
--	P150/25/40	--	--	--	--	--	--
--	P150/35/40	--	--	--	--	--	--

MIX PROPERTIES - PROPORTIONS

P1/ /50

NO.	MIX CODE	WATER kg.	CEMENT kg.	POZZOLAN kg.	F.A. kg.	C.A. kg.	YIELD FACTOR
2	00/00/50	160	320	--	627	1173	1.066
19	P100/05/50	160	320	26	596	1173	1.066
14	P100/15/50	160	320	76	533	1173	1.066
4	P100/25/50	160	320	129	470	1173	1.066
83	P100/35/50	160	320	181	408	1173	1.066
21	P110/00/50	160	288	23	627	1173	1.066
22	P110/05/50	160	288	48	596	1173	1.066
117	P110/15/50	160	288	99	533	1173	1.066
103	P110/25/50	160	288	152	470	1173	1.066
118	P110/35/50	160	288	204	408	1173	1.066
39	P120/00/50	160	256	45	627	1173	1.066
43	P120/05/50	160	256	71	596	1173	1.066
86	P120/15/50	160	256	122	533	1173	1.066
116	P120/25/50	160	256	174	470	1173	1.066
119	P120/35/50	160	256	226	408	1173	1.066
67	P135/00/50	160	208	79	627	1173	1.066
74	P135/05/50	160	208	105	596	1173	1.066
92	P135/15/50	160	208	156	533	1173	1.066
106	P135/25/50	160	208	208	470	1173	1.066
110	P135/35/50	160	208	259	408	1173	1.066
55	P150/00/50	160	160	113	627	1173	1.066
120	P150/05/50	160	160	139	596	1173	1.066
98	P150/15/50	160	160	190	533	1173	1.066
108	P150/25/50	160	160	242	470	1173	1.066
109	P150/35/50	160	160	293	408	1173	1.066

MIX PROPERTIES - PROPORTIONS

P1/ /60

NO.	MIX CODE	WATER kg.	CEMENT kg.	POZZOLAN kg.	F.A. kg.	C.A. kg.	YIELD FACTOR
3	00/00/60	192	320	--	627	1173	1.031
20	P100/05/60	192	320	26	596	1173	1.031
15	P100/15/60	192	320	76	533	1173	1.031
5	P100/25/60	192	320	129	470	1173	1.031
84	P100/35/60	192	320	181	408	1173	1.031
31	P110/00/60	192	288	23	627	1173	1.031
30	P110/05/60	192	288	48	596	1173	1.031
--	P110/15/60	--	--	--	--	--	1.031
--	P110/25/60	--	--	--	--	--	1.031
--	P110/35/60	--	--	--	--	--	1.031
40	P120/00/60	192	256	45	627	1173	1.031
44	P120/05/60	192	256	71	596	1173	1.031
88	P120/15/60	192	256	122	533	1173	1.031
--	P120/25/60	--	--	--	--	--	1.031
--	P120/35/60	--	--	--	--	--	1.031
68	P135/00/60	192	208	79	627	1173	1.031
73	P135/05/60	192	208	105	596	1173	1.031
93	P135/15/60	192	208	156	533	1173	1.031
--	P135/25/60	--	--	--	--	--	1.031
--	P135/35/60	--	--	--	--	--	1.031
57	P150/00/60	192	160	113	627	1173	1.031
--	P150/05/60	--	--	--	--	--	1.031
100	P150/15/60	192	160	190	533	1173	1.031
--	P150/25/60	--	--	--	--	--	1.031
--	P150/35/60	--	--	--	--	--	1.031

MIX PROPERTIES - PROPORTIONS

P2/ /40

NO.	MIX CODE	WATER kg.	CEMENT kg.	POZZOLAN kg.	F.A. kg.	C.A. kg.	YIELD FACTOR
1	00/00/40	128	320	--	627	1173	1.104
36	P200/05/40	128	320	23	596	1173	1.104
10	P200/15/40	128	320	69	533	1173	1.104
7	P200/25/40	128	320	115	470	1173	1.104
79	P200/35/40	128	320	162	408	1173	1.104
26	P210/00/40	128	288	20	627	1173	1.104
27	P210/05/40	128	288	43	596	1173	1.104
--	P210/15/40	--	--	--	--	--	--
--	P210/25/40	--	--	--	--	--	--
--	P210/35/40	--	--	--	--	--	--
46	P220/00/40	128	256	40	627	1173	1.104
49	P220/05/40	128	256	63	596	1173	1.104
--	P220/15/40	--	--	--	--	--	--
--	P220/25/40	--	--	--	--	--	--
--	P220/35/40	--	--	--	--	--	--
71	P235/00/40	128	208	70	627	1173	1.104
76	P235/05/40	128	208	94	596	1173	1.104
95	P235/15/40	128	208	140	533	1173	1.104
--	P235/25/40	--	--	--	--	--	--
--	P235/35/40	--	--	--	--	--	--
60	P250/00/40	128	160	101	627	1173	1.104
61	P250/05/40	128	160	124	596	1173	1.104
101	P250/15/40	128	160	170	533	1173	1.104
--	P250/25/40	--	--	--	--	--	--
--	P250/35/40	--	--	--	--	--	--

MIX PROPERTIES - PROPORTIONS

P2/ /50

NO.	MIX CODE	WATER kg.	CEMENT kg.	POZZOLAN kg.	F.A. kg.	C.A. kg.	YIELD FACTOR
C	00/00/50	160	320	--	627	1173	1.066
35	P200/05/50	160	320	23	596	1173	1.066
11	P200/15/50	160	320	69	533	1173	1.066
8	P200/25/50	160	320	115	470	1173	1.066
80	P200/35/50	160	320	162	408	1173	1.066
24	P210/00/50	160	288	20	627	1173	1.066
25	P210/05/50	160	288	43	596	1173	1.066
121	P210/15/50	160	288	89	533	1173	1.066
122	P210/25/50	160	288	135	470	1173	1.066
123	P210/35/50	160	288	182	408	1173	1.066
47	P220/00/50	160	256	40	627	1173	1.066
51	P220/05/50	160	256	63	596	1173	1.066
89	P220/15/50	160	256	109	533	1173	1.066
115	P220/25/50	160	256	156	470	1173	1.066
124	P220/35/50	160	256	202	408	1173	1.066
70	P235/00/50	160	208	70	627	1173	1.066
77	P235/05/50	160	208	94	596	1173	1.066
96	P235/15/50	160	208	140	533	1173	1.066
113	P235/25/50	160	208	186	470	1173	1.066
111	P235/35/50	160	208	232	408	1173	1.066
59	P250/00/50	160	160	101	627	1173	1.066
62	P250/05/50	160	160	124	596	1173	1.066
102	P250/15/50	160	160	170	533	1173	1.066
114	P250/25/50	160	160	216	470	1173	1.066
112	P250/35/50	160	160	262	408	1173	1.066

<u>MIX PROPERTIES - PROPORTIONS</u>

P2/ /60

NO.	MIX CODE	WATER kg.	CEMENT kg.	POZZOLAN kg.	F.A. kg.	C.A. kg.	YIELD FACTOR
3	00/00/60	192	320	--	627	1173	1.031
34	P200/05/60	192	320	23	596	1173	1.031
12	P200/15/60	192	320	69	533	1173	1.031
9	P200/25/60	192	320	115	470	1173	1.031
81	P200/35/60	192	320	162	408	1173	1.031
--	P210/00/60	--	--	--	--	--	--
32	P210/05/60	192	288	43	596	1173	1.031
--	P210/15/60	--	--	--	--	--	--
--	P210/25/60	--	--	--	--	--	--
--	P210/35/60	--	--	--	--	--	--
48	P220/00/60	192	256	40	627	1173	1.031
50	P220/05/60	192	256	63	596	1173	1.031
90	P220/15/60	192	256	109	533	1173	1.031
--	P220/25/60	--	--	--	--	--	--
--	P220/35/60	--	--	--	--	--	--
69	P235/00/60	192	208	70	627	1173	1.031
78	P235/05/60	192	208	94	596	1173	1.031
99	P235/15/60	192	208	140	533	1173	1.031
--	P235/25/60	--	--	--	--	--	--
--	P235/35/60	--	--	--	--	--	--
58	P250/00/60	192	160	101	627	1173	1.031
63	P250/05/60	192	160	124	596	1173	1.031
103	P250/15/60	192	160	170	533	1173	1.031
--	P250/25/60	--	--	--	--	--	--
--	P250/35/60	--	--	--	--	--	--

APPENDIX II

MIX PROPERTIES - DENSITY

(Theoretical fully compacted)

P1-2/-/40

NO.	MIX CODE	SOLID DENSITY (kg/m3)	NO.	MIX CODE	SOLID DENSITY (kg/m3)
1	00/00/40	2,482	1	00/00/40	2,482
18	P100/05/40	2,476	36	P200/05/40	2,473
13	P100/15/40	2,463	10	P200/15/40	2,454
6	P100/25/40	2,451	7	P200/25/40	2,435
-	P100/35/40	-	79	P200/35/40	2,419
28	P110/00/40	2,472	26	P210/00/40	2,469
29	P110/05/40	2,465	27	P210/05/40	2,460
-	P110/15/40	-	-	P210/15/40	-
-	P110/25/40	-	-	P210/25/40	-
-	P110/35/40	-	-	P210/35/40	-
41	P120/00/40	2,461	46	P220/00/40	2,455
42	P120/05/40	2,455	49	P220/05/40	2,446
85	P120/15/40	2,442	-	P220/15/40	-
-	P120/25/40	-	-	P220/25/40	-
-	P120/35/40	-	-	P220/35/40	-
66	P135/00/40	2,445	71	P235/00/40	2,435
75	P135/05/40	2,440	76	P235/05/40	2,428
91	P135/15/40	2,427	95	P235/15/40	2,409
-	P135/25/40	-	-	P235/25/40	-
-	P135/35/40	-	-	P235/35/40	-
56	P150/00/40	2,430	60	P250/00/40	2,417
-	P150/05/40	-	61	P250/05/40	2,408
97	P150/15/40	2,411	101	P250/15/40	2,389
-	P150/25/40	-	-	P250/25/40	-
-	P150/35/40	-	-	P250/35/40	-

MIX PROPERTIES - DENSITY

P1-2/-/50

NO.	MIX CODE	SOLID DENSITY (kg/m3)	NO.	MIX CODE	SOLID DENSITY (kg/m3)
C	00/00/50	2,430	C	00/00/50	2,430
19	P100/05/50	2,425	35	P200/05/50	2,423
14	P100/15/50	2,412	11	P200/15/50	2,405
4	P100/25/50	2,400	8	P200/25/50	2,387
83	P100/35/50	2,390	80	P200/35/50	2,371
21	P110/00/50	2,421	24	P210/00/50	2,419
22	P110/05/50	2,414	25	P210/05/50	2,410
117	P110/15/50	2,403	121	P210/15/50	2,392
107	P110/25/50	2,391	122	P210/25/50	2,374
118	P110/35/50	2,379	123	P210/35/50	2,357
39	P120/00/50	2,410	47	P220/00/50	2,406
43	P120/05/50	2,405	51	P220/05/50	2,397
86	P120/15/50	2,392	89	P220/15/50	2,379
116	P120/25/50	2,381	115	P220/25/50	2,362
119	P120/35/50	2,370	124	P220/35/50	2,345
67	P135/00/50	2,396	70	P235/00/50	2,387
74	P135/05/50	2,390	77	P235/05/50	2,379
92	P135/15/50	2,378	96	P235/15/50	2,361
106	P135/25/50	2,365	113	P235/25/50	2,343
109	P135/35/50	2,352	111	P235/35/50	2,326
55	P150/00/50	2,381	59	P250/00/50	2,368
120	P150/05/50	2,375	62	P250/05/50	2,360
98	P150/15/50	2,363	102	P250/15/50	2,342
108	P150/25/50	2,351	114	P250/25/50	2,324
110	P150/35/50	2,339	112	P250/35/50	2,307

MIX PROPERTIES - DENSITY

P1-2/-/60

NO.	MIX CODE	SOLID DENSITY (kg/m3)	NO.	MIX CODE	SOLID DENSITY (kg/m3)
3	00/00/60	2,384	3	00/00/60	2,384
20	P100/05/60	2,378	34	P200/05/60	2,376
15	P100/15/60	2,366	12	P200/15/60	2,358
5	P100/25/60	2,355	9	P200/25/60	2,341
84	P100/35/60	2,344	81	P200/35/60	2,325
31	P110/00/60	2,374	-	P210/00/60	-
30	P110/05/60	2,368	32	P210/05/60	2,363
-	P110/15/60	-	-	P210/15/60	-
-	P110/25/60	-	-	P210/25/60	-
-	P110/35/60	-	-	P210/35/60	-
40	P120/00/60	2,364	48	P220/00/60	2,359
44	P120/05/60	2,359	50	P220/05/60	2,351
88	P120/15/60	2,346	90	P220/15/60	2,334
-	P120/25/60	-	-	P220/25/60	-
-	P120/35/60	-	-	P220/35/60	-
68	P135/00/60	2,350	69	P235/00/60	2,341
73	P135/05/60	2,344	78	P235/05/60	2,333
93	P135/15/60	2,332	99	P235/15/60	2,316
-	P135/25/60	-	-	P235/25/60	-
-	P135/35/60	-	-	P235/35/60	-
57	P150/00/60	2,335	58	P250/00/60	2,323
-	P150/05/60	-	63	P250/05/60	2,315
100	P150/15/60	2,318	103	P250/15/60	2,297
-	P150/25/60	-	-	P250/25/60	-
-	P150/35/60	-	-	P250/35/60	-

A P P E N D I X   III

MIX PROPERTIES - WORKABILITY

(Slump, VeBe, Compacting
Factor and 2 point test)

MIX PROPERTIES - WORKABILITY

CONTROL (00/00/50)

NO.	MIX CODE	SLUMP (mm)	VeBe (secs)	COMPACTING FACTOR	2 POINT TEST	
					YIELD	SLOPE
2	00/00/50	10	9.9	0.872	38.8	17.9
16	00/00/50	25	4.3	0.912	-	-
17	00/00/50	25	4.2	0.876	-	-
33	00/00/50	15	7.0	0.880	-	-
37	00/00/50	65	2.3	0.940	-	-
38	00/00/50	30	5.8	0.900	-	-
52	00/00/50	55	1.5	0.950	-	-
53	00/00/50	50	2.4	0.920	-	-
54	00/00/50	30	5.0	0.910	71.8	15.4
65	00/00/50	40	4.9	0.890	50.6	21.0
104	00/00/50	50	4.3	0.915	40.8	18.8
105	00/00/50	25	4.4	0.900	47.0	19.2
	Mean	35	4.7	0.905	49.8	18.5
	Std. Dev.	17.0	2.25	0.024	13.2	2.0
	Coefficient of variation					
	%	48	48	3	26	11
	Units	mm	secs		Nm	$(Nms)^{-1}$

P1/-/40

NO.	MIX CODE	SLUMP (mm)	VeBe (secs)	COMPACTING FACTOR	2 POINT TEST	
					YIELD	SLOPE
1	00/00/40	0	78.6	0.746	67.5	19.3
18	P100/05/40	0	55.7	0.733	75.1	19.3
13	P100/15/40	0	45.1	0.689	81.5	19.4
6	P100/25/40	0	106.0	0.637	91.9	25.9
-	P100/35/40	-	-	-	-	-
28	P110/00/40	0 - 5	21.3	0.768	63.8	17.0
29	P110/05/40	0 - 5	25.8	0.748	79.7	10.5
-	P110/15/40	-	-	-	-	-
-	P110/25/40	-	-	-	-	-
-	P110/35/40	-	-	-	-	-
41	P120/00/40	0	39.2	0.770	56.4	14.4
42	P120/05/40	5	16.5	0.800	57.8	18.8
-	P120/15/40	-	-	-	-	-
-	P120/25/40	-	-	-	-	-
-	P120/35/40	-	-	-	-	-
66	P135/00/40	0	23.2	0.760	89.6	25.9
75	P135/05/40	0	17.6	0.755	75.8	28.6
91	P135/15/40	0	19.1	0.752	63.5	39.9
-	P135/25/40	-	-	-	-	-
-	P135/35/40	-	-	-	-	-
56	P130/00/40	5 - 10	13.8	0.820	84.6	23.8
-	P150/05/40	-	-	-	-	-
97	P150/15/40	0	23.7	0.706	103.4	23.5
-	P150/25/40	-	-	-	-	-
-	P150/35/40	-	-	-	-	-

MIX PROPERTIES - WORKABILITY

P1/-/50

NO.	MIX CODE	SLUMP (mm)	VeBe (secs)	COMPACTING FACTOR	2 POINT TEST	
					YIELD	SLOPE
C	00/00/50	35	4.7	0.905	49.8	18.5
19	P100/05/50	30	5.3	0.898	40.2	7.9
14	P100/15/50	60	3.8	0.890	33.9	8.0
4	P100/25/50	15	8.8	0.811	48.9	5.7
83	P100/35/50	10	8.6	0.738	101.2	16.2
21	P110/00/50	Coll	1.8	0.953	38.5	5.5
22	P110/05/50	Coll	1.8	0.967	32.7	5.3
117	P110/15/50	-	-	0.920	-	-
107	P110/25/50	50	4.9	0.878	60.4	22.0
118	P110/35/50	-	-	0.805	-	-
39	P120/00/50	42.5	3.2	0.920	28.3	6.9
43	P120/05/50	60	2.1	0.940	34.3	7.4
86	P120/15/50	50	3.6	0.900	39.3	20.3
116	P120/25/50	35	4.8	0.859	58.0	23.1
119	P120/35/50	-	-	0.770	-	-
67	P135/00/50	80	2.5	0.950	44.8	7.9
74	P135/05/50	Coll	1.9	0.955	34.8	12.3
92	P135/15/50	80	1.1	0.927	91.8	21.0
106	P135/25/50	45	3.6	0.871	52.2	23.9
110	P135/35/50	40	6.5	0.788	87.0	20.2
55	P150/00/50	Coll	1.0	0.960	19.6	15.8
120	P150/05/50	-	-	0.950	-	-
98	P150/15/50	100	1.7	0.936	66.7	3.3
108	P150/25/50	75	2.8	0.923	68.5	12.1
109	P150/35/50	15	8.1	0.738	109.4	14.2

P1/-/60

NO.	MIX CODE	SLUMP (mm)	VeBe (secs)	COMPACTING FACTOR	2 POINT TEST	
					YIELD	SLOPE
3	00/00/60	Coll	1.6	0.946	29.8	6.4
20	P100/05/60	Coll	1.1	0.986	10.5	5.4
15	P100/15/60	Coll	1.5	0.980	-	-
5	P100/25/60	Coll	1.7	0.959	20.5	2.3
84	P100/35/60	110 Shear	1.2	0.976	25.2	10.1
31	P110/00/60	Coll	1.3	0.980	3.8	7.2
30	P110/05/60	Coll	1.1	0.980	11.9	3.6
-	P110/15/60	-	-	-	-	-
-	P110/25/60	-	-	-	-	-
-	P110/35/60	-	-	-	-	-
40	P120/00/60	Coll	0.9	0.990	2.3	7.4
44	P120/05/60	Coll	1.0	0.990	3.3	6.8
88	P120/15/60	Coll	0.8	0.984	16.5	4.9
-	P120/25/60	-	-	-	-	-
-	P120/35/60	-	-	-	-	-
68	P135/00/60	Coll	0.8	0.990	0	10.1
73	P135/05/60	Coll	0.5	0.990	3.5	10.3
93	P135/15/60	Coll	0.5	0.990	4.6	7.1
-	P135/25/60	-	-	-	-	-
-	P135/35/60	-	-	-	-	-
57	P150/00/60	Coll	0.9	0.987	0	11.1
-	P150/05/60	-	-	-	-	-
100	P150/15/60	Coll	0.4	0.990	18.4	3.4
-	P150/25/60	-	-	-	-	-
-	P150/35/60	-	-	-	-	-

P2/-/40

NO.	MIX CODE	SLUMP (mm)	VeBe (secs)	COMPACTING FACTOR	2 POINT TEST	
					YIELD	SLOPE
1	00/00/40	0	78.6	0.746	67.5	19.3
36	P200/05/40	0	16.8	0.790	57.6	22.1
10	P200/15/40	0	64.3	0.709	84.4	20.7
7	P200/25/40	0	208.2	0.667	59.0	36.2
79	P200/35/40	0	516.5	0.710	98.7	25.8
26	P210/00/40	0	21.0	0.775	-	-
27	P210/05/40	0	44.8	0.740	66.0	19.2
-	P210/15/40	-	-	-	-	-
-	P210/25/40	-	-	-	-	-
-	P210/35/40	-	-	-	-	-
46	P220/00/40	0	14.4	0.810	72.5	19.7
49	P220/05/40	0	17.9	0.790	71.2	17.0
-	P220/15/40	-	-	-	-	-
-	P220/25/40	-	-	-	-	-
-	P220/35/40	-	-	-	-	-
71	P235/00/40	0	24.0	0.730	73.2	35.5
76	P235/05/40	0	21.7	0.768	64.1	39.3
95	P235/15/40	0	67.0	0.724	87.9	35.7
-	P235/25/40	-	-	-	-	-
-	P235/35/40	-	-	-	-	-
60	P250/00/40	0	19.5	0.800	70.4	35.5
61	P250/05/40	12.5	8.8	0.850	62.2	35.2
101	P250/15/40	0	52.7	0.731	82.5	38.8
-	P250/25/40	-	-	-	-	-
-	P250/35/40	-	-	-	-	-

MIX PROPERTIES - WORKABILITY

P2/-/50

NO.	MIX CODE	SLUMP (mm)	VeBe (secs)	COMPACTING FACTOR	2 POINT TEST	
					YIELD	SLOPE
C	00/00/50	35	4.7	0.905	49.8	18.5
35	P200/05/50	40	3.3	0.920	32.1	10.2
11	P200/15/50	30	5.7	0.880	84.4	20.7
8	P200/25/50	15	10.4	0.807	39.3	13.4
80	P200/35/50	0	14.0	0.745	98.1	58.6
24	P210/00/50	37.5	2.5	0.932	35.8	10.8
25	P210/05/50	45	2.8	0.923	28.1	10.2
121	P210/15/50	-	-	0.860	-	-
122	P210/25/50	-	-	0.780	-	-
123	P210/35/50	-	-	0.715	-	-
47	P220/00/50	Coll	1.6	0.950	35.2	14.3
51	P220/05/50	Coll	2.2	0.960	37.6	10.9
89	P220/15/50	35	4.4	0.973	38.7	30.7
115	P220/25/50	10	8.0	0.781	89.1	14.8
124	P220/35/50	-	-	0.718	-	-
70	P235/00/50	47.5	4.4	0.910	48.2	25.2
77	P235/05/50	42.5	3.3	0.912	47.4	16.0
96	P235/15/50	40	3.8	0.883	65.7	13.6
113	P235/25/50	5	6.2	0.803	86.2	15.3
111	P235/35/50	0	10.3	0.736	93.9	21.4
59	P250/00/50	70	2.6	0.930	34.2	24.0
62	P250/05/50	50	2.4	0.940	33.0	21.9
102	P250/15/50	25	4.8	0.876	70.4	18.9
114	P250/25/50	25	6.0	0.807	79.5	16.6
112	P250/35/50	0	8.4	0.737	93.9	21.5

MIX PROPERTIES - WORKABILITY

P2/-/60

NO.	MIX CODE	SLUMP (mm)	VeBe (secs)	COMPACTING FACTOR	2 POINT TEST	
					YIELD	SLOPE
3	00/00/60	Coll	1.6	0.946	29.8	6.4
34	P200/05/60	Coll	1.2	0.970	5.6	6.0
12	P200/05/60	Coll	1.4	0.992	11.4	4.9
9	P200/25/60	Coll	1.5	0.981	18.7	3.5
81	P200/35/60	85	2.5	0.938	42.9	10.1
-	P210/00/60	-	-	-	-	-
32	P210/05/60	Coll	1.0	0.980	11.6	4.2
-	P210/15/60	-	-	-	-	-
-	P210/25/60	-	-	-	-	-
-	P210/35/60	-	-	-	-	-
48	P220/00/60	Coll	0.6	0.990	15.8	4.6
50	P220/05/60	Coll	0.8	0.990	10.0	5.7
90	P220/15/60	Coll	1.3	0.981	11.2	8.5
-	P220/25/60	-	-	-	-	-
-	P220/35/60	-	-	-	-	-
69	P235/00/60	Coll	0.7	0.980	5.2	9.4
78	P235/05/60	Coll	0.4	0.990	0.1	8.8
99	P235/15/60	Coll	0.5	0.998	13.4	5.0
-	P235/25/60	-	-	-	-	-
-	P235/35/60	-	-	-	-	-
58	P250/00/60	Coll	0.8	0.984	4.7	10.0
63	P250/05/60	Coll	0.5	0.990	0	10.3
103	P250/15/60	Coll	0.4	0.990	4.9	8.3
-	P250/25/60	-	-	-	-	-
-	P250/35/60	-	-	-	-	-

A P P E N D I X IV

MIX PROPERTIES - STRENGTH

(Compressive and indirect tensile
strength tests and ultra-sonic
pulse velocity non-destructive test)

MIX PROPERTIES - STRENGTH (7 days)

CONTROL (00/00/50)

NO.	MIX CODE	COMP. STRENGTH (N/mm2)	INDIRECT TENSILE STRENGTH (N/mm2)	U.S.P.V. (km/sec)	COMP. STRENGTH % 28 DAY CONTROL	INDIRECT TENSILE STRENGTH % 28 DAY CONTROL	U.S.P.V. % 28 DAY CONTROL
2	00/00/50	34.7	3.31	4.587	66	85	97
16	"	41.4	3.50	4.643	79	90	98
17	"	37.0	3.37	4.587	71	86	97
33	"	38.0	3.39	4.566	73	86	96
37	"	34.8	3.21	4.545	67	82	96
38	"	37.4	3.18	4.621	71	82	98
52	"	33.6	2.77	4.566	64	71	96
53	"	35.6	3.24	4.598	68	83	97
54	"	41.1	3.37	4.651	79	86	98
65	"	40.2	3.15	4.662	77	81	98
104	"	34.5	2.86	4.545	66	73	96
105	"	36.2	2.90	-	69	74	-
	Mean	37.0	3.18	4.597			
	Std. Dev.	2.7	0.23	0.042			
	Coefficient of variat'n						
	%	7.2	11.8	0.9			

MIX PROPERTIES - STRENGTH (28 days)

CONTROL (00/00/50)

NO.	MIX CODE	COMP. STRENGTH (N/mm^2)	INDIRECT TENSILE STRENGTH (N/mm^2)	U.S.P.V. (km/sec)	COMP. STRENGTH % 28 DAY CONTROL	INDIRECT TENSILE STRENGTH % 28 DAY CONTROL	U.S.P.V. % 28 DAY CONTROL
2	00/00/50	44.8	4.17	4.753	86	107	100
16	"	55.2	3.82	4.776	105	98	101
17	"	53.8	3.85	4.739	103	99	100
33	"	55.6	3.85	4.739	106	99	100
37	"	49.5	3.76	4.704	95	96	99
38	"	56.3	4.10	4.739	108	105	100
52	"	48.3	3.91	4.785	92	100	101
53	"	51.8	3.85	4.773	99	99	101
54	"	55.2	4.20	4.794	105	108	101
65	"	58.1	3.79	4.785	111	97	101
104	"	49.6	3.72	4.630	95	95	98
105	"	49.8	3.79	4.651	95	97	98
	Mean	52.33	3.90	4.739			
	Std. Dev.	4.0	0.16	0.053			
	Coefficient of variat'n						
	%	7.9	6.9	1.1			

MIX PROPERTIES - STRENGTH (91 days)

CONTROL (00/00/50)

NO.	MIX CODE	COMP. STRENGTH (N/mm2)	INDIRECT TENSILE STRENGTH (N/mm2)	U.S.P.V. (km/sec)	COMP. STRENGTH % 28 DAY CONTROL	INDIRECT TENSILE STRENGTH % 28 DAY CONTROL	U.S.P.V. % 28 DAY CONTROL
2	00/00/50	52.8	4.36	4.854	101	112	102
16	"	64.5	-	-	123	-	-
17	"	60.4	-	-	115	-	-
33	"	68.0	4.10	4.831	130	105	102
37	"	57.5	3.88	4.831	110	99	102
38	"	61.4	4.01	4.843	117	103	102
52	"	55.6	4.01	4.843	106	103	102
53	"	58.8	4.39	4.831	112	113	102
54	"	61.7	4.01	4.831	118	103	102
65	"	66.1	4.42	-	126	113	-
104	"	57.3	4.01	4.762	109	103	100
105	"	56.7	3.92	4.762	108	101	100
	Mean	60.1	4.11	4.822			
	Std. Dev.	4.500	0.200	0.032			
	Coefficient of variat'n						
	%	7.5	8.1	0.7			

MIX PROPERTIES - STRENGTH (7 days)

P1/-/40

NO.	MIX CODE	COMP. STRENGTH (N/mm^2)	INDIRECT TENSILE STRENGTH (N/mm^2)	U.S.P.V. (km/sec)	COMP. STRENGTH % 28 DAY CONTROL	INDIRECT TENSILE STRENGTH % 28 DAY CONTROL	U.S.P.V. % 28 DAY CONTROL
1	00/00/40	56.1	4.17	4.776	107	107	101
18	P100/05/40	56.0	4.11	4.730	107	105	100
13	P100/15/40	58.6	3.98	4.831	112	102	102
6	P100/25/40	49.5	3.85	4.739	96	99	100
-	P100/35/40	-	-	-	-	-	-
28	P110/00/40	47.7	3.50	4.739	91	90	100
29	P110/05/40	47.6	3.66	4.717	91	94	100
-	P110/15/40	-	-	-	-	-	-
-	P110/25/40	-	-	-	-	-	-
-	P110/35/40	-	-	-	-	-	-
41	P120/00/40	46.7	3.25	4.708	89	83	99
42	P120/05/40	45.8	3.47	4.739	88	89	100
85	P120/15/40	40.1	3.40	4.738	77	87	100
-	P120/25/40	-	-	-	-	-	-
-	P120/35/40	-	-	-	-	-	-
66	P135/00/40	35.7	3.06	4.619	68	78	97
75	P135/05/40	33.9	2.86	4.619	65	73	97
91	P135/15/40	30.3	3.53	4.640	58	91	98
-	P135/25/40	-	-	-	-	-	-
-	P135/35/40	-	-	-	-	-	-
56	P150/00/40	22.4	2.07	4.545	43	53	96
-	P150/05/40	-	-	-	-	-	-
97	P150/15/40	23.1	2.32	4.464	44	59	94
-	P150/25/40	-	-	-	-	-	-
-	P150/35/40	-	-	-	-	-	-

MIX PROPERTIES - STRENGTH (28 days)

P1/-/40

NO.	MIX CODE	COMP. STRENGTH (N/mm2)	INDIRECT TENSILE STRENGTH (N/mm2)	U.S.P.V. (km/sec)	COMP. STRENGTH % 28 DAY CONTROL	INDIRECT TENSILE STRENGTH % 28 DAY CONTROL	U.S.P.V. % 28 DAY CONTROL
1	00/00/40	63.9	4.96	4.892	122	127	103
18	P100/05/40	72.9	4.20	4.887	139	103	103
13	P100/15/40	74.0	4.77	4.878	141	122	103
6	P100/25/40	61.6	4.61	4.869	118	118	103
-	P100/35/40	-	-	-	-	-	-
28	P110/00/40	62.2	4.33	4.878	119	111	103
29	P110/05/40	65.0	4.49	4.831	124	115	102
-	P110/15/40	-	-	-	-	-	-
-	P110/25/40	-	-	-	-	-	-
-	P110/35/40	-	-	-	-	-	-
41	P120/00/40	62.8	4.14	4.831	120	106	102
42	P120/05/40	62.4	4.46	4.831	119	114	102
85	P120/15/40	51.1	4.36	4.785	98	112	101
-	P120/25/40	-	-	-	-	-	-
-	P120/35/40	-	-	-	-	-	-
66	P135/00/40	53.9	3.76	4.717	103	96	100
75	P135/05/40	52.2	3.66	4.773	100	94	107
91	P135/15/40	43.1	3.60	4.739	82	92	100
-	P135/25/40	-	-	-	-	-	-
-	P135/35/40	-	-	-	-	-	-
56	P150/00/40	36.5	2.96	4.695	70	76	99
-	P150/05/40	-	-	-	-	-	-
97	P150/15/40	40.0	3.12	4.598	76	80	97
-	P150/25/40	-	-	-	-	-	-
-	P150/35/40	-	-	-	-	-	-

P1/-/40

NO.	MIX CODE	COMP. STRENGTH (N/mm2)	INDIRECT TENSILE STRENGTH (N/mm2)	U.S.P.V. (km/sec)	COMP. STRENGTH % 28 DAY CONTROL	INDIRECT TENSILE STRENGTH % 28 DAY CONTROL	U.S.P.V. % 28 DAY CONTROL
1	00/00/40	75.1	5.19	4.990	144	133	105
18	P100/05/40	80.9	4.84	4.975	155	124	105
13	P100/15/40	81.5	5.28	5.000	156	135	106
6	P100/25/40	70.1	4.96	4.950	134	127	104
-	P100/35/40	-	-	-	-	-	-
28	P110/00/40	74.8	4.71	4.936	143	121	104
29	P110/05/40	75.2	4.77	4.950	144	122	104
-	P110/15/40	-	-	-	-	-	-
-	P110/25/40	-	-	-	-	-	-
-	P110/35/40	-	-	-	-	-	-
41	P120/00/40	73.0	4.58	4.926	139	117	104
42	P120/05/40	71.5	4.68	4.926	137	120	104
85	P120/15/40	-	-	-	-	-	-
-	P120/25/40	-	-	-	-	-	-
-	P120/35/40	-	-	-	-	-	-
66	P135/00/40	58.6	4.33	4.869	112	111	103
75	P135/05/40	65.8	4.65	4.902	126	119	103
91	P135/15/40	57.3	4.79	4.831	109	122	102
-	P135/25/40	-	-	-	-	-	-
-	P135/35/40	-	-	-	-	-	-
56	P150/00/40	46.3	3.79	4.780	88	97	101
-	P150/05/40	-	-	-	-	-	-
97	P150/15/40	59.0	3.50	4.762	113	90	100
-	P150/25/40	-	-	-	-	-	-
-	P150/35/40	-	-	-	-	-	-

MIX PROPERTIES - STRENGTH (7 days)

P2/ /40

NO.	MIX CODE	COMP. STRENGTH (N/mm2)	INDIRECT TENSILE STRENGTH (N/mm2)	U.S.P.V. (km/sec)	COMP. STRENGTH % 28 DAY CONTROL	INDIRECT TENSILE STRENGTH % 28 DAY CONTROL	U.S.P.V. % 28 DAY CONTROL
1	00/00/40	56.1	4.17	4.776	107	107	101
36	P200/05/40	55.6	3.82	4.739	106	98	100
10	P200/15/40	58.9	4.65	4.739	113	119	100
7	P200/25/40	53.4	4.23	4.695	102	108	99
79	P200/35/40	48.3	3.82	4.662	92	98	98
26	P210/00/40	44.4	3.60	4.695	85	92	99
27	P210/05/40	50.6	3.79	4.739	97	97	100
-	P210/15/40	-	-	-	-	-	-
-	P210/25/40	-	-	-	-	-	-
-	P210/35/40	-	-	-	-	-	-
46	P220/00/40	43.4	3.25	4.695	83	83	100
49	P220/05/40	43.3	3.31	4.651	83	85	98
-	P220/15/40	-	-	-	-	-	-
-	P220/25/40	-	-	-	-	-	-
-	P220/35/40	-	-	-	-	-	-
71	P235/00/40	32.8	2.99	4.598	63	77	97
76	P235/05/40	32.0	2.99	4.525	61	77	95
95	P235/15/40	34.5	2.86	4.515	66	73	95
-	P235/25/40	-	-	-	-	-	-
-	P235/35/40	-	-	-	-	-	-
60	P250/00/40	22.1	2.13	4.517	42	55	95
61	P250/05/40	16.7	1.75	4.405	32	45	93
101	P250/15/40	20.3	2.13	4.367	39	55	92
-	P250/25/40	-	-	-	-	-	-
-	P250/35/40	-	-	-	-	-	-

MIX PROPERTIES - STRENGTH (28 days)

P2/-/40

NO.	MIX CODE	COMP. STRENGTH (N/mm2)	INDIRECT TENSILE STRENGTH (N/mm2)	U.S.P.V. (km/sec)	COMP. STRENGTH % 28 DAY CONTROL	INDIRECT TENSILE STRENGTH % 28 DAY CONTROL	U.S.P.V. % 28 DAY CONTROL
1	00/00/40	63.9	4.96	4.892	122	137	103
36	P200/05/40	71.6	4.52	4.869	137	116	103
10	P200/15/40	72.2	4.87	4.808	138	125	101
7	P200/25/40	68.6	4.52	4.831	131	116	102
79	P200/35/40	57.6	3.95	4.739	110	101	100
26	P210/00/40	64.0	4.14	4.831	122	106	102
27	P210/05/40	67.3	4.46	4.831	129	114	102
-	P210/15/40	-	-	-	-	-	-
-	P210/25/40	-	-	-	-	-	-
-	P210/35/40	-	-	-	-	-	-
46	P220/00/40	58.9	4.23	4.822	113	108	102
49	P220/05/40	57.7	4.26	4.785	110	109	101
-	P220/15/40	-	-	-	-	-	-
-	P220/25/40	-	-	-	-	-	-
-	P220/35/40	-	-	-	-	-	-
71	P235/00/40	48.7	3.56	4.706	93	91	99
76	P235/05/40	47.3	3.60	4.695	90	92	99
95	P235/15/40	48.0	3.69	4.630	92	95	98
-	P235/25/40	-	-	-	-	-	-
-	P235/35/40	-	-	-	-	-	-
60	P250/00/40	35.6	3.15	4.650	68	81	98
61	P250/05/40	26.2	2.58	4.587	50	66	98
101	P250/15/40	32.5	2.83	4.515	62	73	95
-	P250/25/40	-	-	-	-	-	-
-	P250/35/40	-	-	-	-	-	-

MIX PROPERTIES - STRENGTH (91 days)

P2/-/40

NO.	MIX CODE	COMP. STRENGTH (N/mm2)	INDIRECT TENSILE STRENGTH (N/mm2)	U.S.P.V. (km/sec)	COMP. STRENGTH % 28 DAY CONTROL	INDIRECT TENSILE STRENGTH % 28 DAY CONTROL	U.S.P.V. % 28 DAY CONTROL
1	00/00/40	75.1	5.19	4.990	144	133	105
36	P200/05/40	80.5	4.64	4.926	154	119	104
10	P200/15/40	83.6	5.19	4.965	160	133	105
7	P200/25/40	75.8	5.38	4.926	145	138	104
79	P200/35/40	61.1	4.52	4.831	117	116	102
26	P210/00/40	70.2	4.74	4.886	134	122	103
27	P210/05/40	75.1	4.71	4.950	144	121	104
-	P210/15/40	-	-	-	-	-	-
-	P210/25/40	-	-	-	-	-	-
-	P210/35/40	-	-	-	-	-	-
46	P220/00/40	66.1	4.36	4.914	126	112	104
49	P220/05/40	70.6	4.30	4.902	135	110	103
-	P220/15/40	-	-	-	-	-	-
-	P220/25/40	-	-	-	-	-	-
-	P220/35/40	-	-	-	-	-	-
71	P235/00/40	56.6	4.11	4.695	108	105	99
76	P235/05/40	59.4	3.85	4.762	114	99	100
95	P235/15/40	62.1	4.20	4.739	119	108	100
-	P235/25/40	-	-	-	-	-	-
-	P235/35/40	-	-	-	-	-	-
60	P250/00/40	46.4	3.60	4.785	89	92	101
61	P250/05/40	35.9	3.31	4.717	69	85	100
101	P250/15/40	44.6	3.50	4.695	85	90	99
-	P250/25/40	-	-	-	-	-	-
-	P250/35/40	-	-	-	-	-	-

P1/-/50

NO.	MIX CODE	COMP. STRENGTH (N/mm^2)	INDIRECT TENSILE STRENGTH (N/mm^2)	U.S.P.V. (km/sec)	COMP. STRENGTH % 28 DAY CONTROL	INDIRECT TENSILE STRENGTH % 28 DAY CONTROL	U.S.P.V. % 28 DAY CONTROL
C	00/00/50	37.0	3.18	4.597	71	82	97
19	P100/05/50	35.0	3.25	4.590	67	83	97
14	P100/15/50	41.4	3.66	4.579	79	94	97
4	P100/25/50	34.9	3.25	4.545	67	83	96
83	P100/35/50	40.1	3.34	4.545	77	86	96
21	P110/00/50	28.7	2.70	4.517	55	69	95
22	P110/05/50	27.4	2.67	4.505	52	68	95
-	P110/15/50	-	-	-	-	-	-
107	P110/25/50	35.9	2.99	4.444	69	77	94
-	P110/35/50	-	-	-	-	-	-
39	P120/00/50	28.4	2.70	4.484	54	69	95
43	P120/05/50	26.6	2.67	4.449	51	68	94
86	P120/15/50	25.7	2.61	4.525	49	67	95
116	P120/25/50	32.2	2.80	4.525	62	72	95
-	P120/35/50	-	-	-	-	-	-
67	P135/00/50	18.3	1.91	3.478	35	49	
74	P135/05/50	25.0	2.61	4.444	48	67	94
92	P135/15/50	19.7	2.07	4.367	38	53	92
106	P135/25/50	30.8	2.80	4.505	59	72	95
110	P135/35/50	22.4	2.16	4.357	43	55	92
55	P150/00/50	11.3	1.34	4.237	22	34	89
-	P150/05/50	-	-	-	-	-	-
98	P150/15/50	12.5	1.53	4.175	24	39	88
108	P150/25/50	14.1	1.50	4.158	27	38	88
109	P150/35/50	15.2	1.62	4.090	29	42	86

MIX PROPERTIES - STRENGTH (28 days)

P1/-/50

NO.	MIX CODE	COMP. STRENGTH (N/mm2)	INDIRECT TENSILE STRENGTH (N/mm2)	U.S.P.V. (km/sec)	COMP. STRENGTH % 28 DAY CONTROL	INDIRECT TENSILE STRENGTH % 28 DAY CONTROL	U.S.P.V. % 28 DAY CONTROL
C	00/00/50	52.3	3.90	4.739	100	100	100
19	P100/05/50	52.9	3.91	4.740	101	100	100
14	P100/15/50	53.2	4.01	4.817	102	103	102
4	P100/25/50	50.7	3.82	4.878	97	98	103
83	P100/35/50	60.1	4.04	4.728	115	104	100
21	P110/00/50	43.0	3.37	4.651	82	86	98
22	P110/05/50	41.2	3.53	4.695	79	91	99
-	P110/15/50	-	-	-	-	-	-
107	P110/25/50	49.9	3.76	4.608	95	96	97
-	P110/35/50	-	-	-	-	-	-
39	P120/00/50	42.2	3.50	4.651	81	90	98
43	P120/05/50	42.6	3.47	4.630	81	89	98
86	P120/15/50	38.9	3.60	4.640	74	92	98
116	P120/25/50	53.2	3.82	4.608	102	98	97
-	P120/35/50	-	-	-	-	-	-
67	P135/00/50	33.4	2.86	4.484	64	73	95
74	P135/05/50	32.9	2.80	4.651	63	72	98
92	P135/15/50	31.6	2.70	4.535	60	69	96
106	P135/25/50	47.3	3.95	4.598	90	101	97
110	P135/35/50	36.7	3.15	4.454	70	81	94
55	P150/00/50	19.8	2.00	4.484	38	51	95
-	P150/05/50	-	-	-	-	-	-
98	P150/15/50	22.9	2.32	4.376	44	59	92
108	P150/25/50	25.3	2.35	4.292	48	60	91
109	P150/35/50	27.8	2.64	4.348	52	68	92

P1/-/50

NO.	MIX CODE	COMP. STRENGTH (N/mm2)	INDIRECT TENSILE STRENGTH (N/mm2)	U.S.P.V. (km/sec)	COMP. STRENGTH % 28 DAY CONTROL	INDIRECT TENSILE STRENGTH % 28 DAY CONTROL	U.S.P.V. % 28 DAY CONTROL
C	00/00/50	60.1	4.11	4.822	115	105	102
19	P100/05/50	63.9	4.46	4.808	122	114	101
14	P100/15/50	67.8	4.55	4.854	130	117	102
4	P100/25/50	63.3	4.90	4.888	121	126	103
83	P100/35/50	73.7	4.27	4.785	141	109	101
21	P110/00/50	51.7	3.95	4.785	99	101	101
22	P110/05/50	53.4	3.66	4.739	102	94	100
-	P110/15/50	-	-	-	-	-	-
107	P110/25/50	64.6	4.30	4.739	123	110	100
-	P110/35/50	-	-	-	-	-	-
39	P120/00/50	54.1	4.07	4.773	103	104	101
43	P120/05/50	51.0	4.11	4.739	97	105	100
86	P120/15/50	51.7	4.46	4.785	98	114	101
116	P120/25/50	63.2	4.33	4.739	121	111	100
-	P120/35/50	-	-	-	-	-	-
67	P135/00/50	45.8	3.63	4.515	88	93	95
74	P135/05/50	45.0	3.72	4.762	86	95	100
92	P135/15/50	44.8	3.31	4.651	86	85	98
106	P135/25/50	62.5	5.16	4.739	119	132	100
110	P135/35/50	50.4	4.04	4.608	96	104	97
55	P150/00/50	28.7	3.06	4.608	55	78	97
-	P150/05/50	-	-	-	-	-	-
98	P150/15/50	33.4	3.44	4.608	64	88	97
108	P150/25/50	36.2	3.50	4.566	69	90	96
109	P150/35/50	37.4	3.47	4.555	71	89	96

MIX PROPERTIES - STRENGTH (7 day)

P2/-/50

NO.	MIX CODE	COMP. STRENGTH (N/mm2)	INDIRECT TENSILE STRENGTH (N/mm2)	U.S.P.V. (km/sec)	COMP. STRENGTH % 28 DAY CONTROL	INDIRECT TENSILE STRENGTH % 28 DAY CONTROL	U.S.P.V. % 28 DAY CONTROL
C	00/00/50	37.0	3.18	4.597	71	82	97
35	P200/05/50	37.1	3.15	4.545	71	81	96
11	P200/15/50	40.4	3.37	4.608	77	86	97
8	P200/25/50	37.6	3.09	4.566	72	79	96
80	P200/35/50	37.6	3.05	4.505	72	78	95
24	P210/00/50	31.7	2.90	4.517	61	74	95
25	P210/05/50	29.9	2.61	4.525	57	67	95
-	P210/15/50	-	-	-	-	-	-
-	P210/25/50	-	-	-	-	-	-
-	P210/35/50	-	-	-	-	-	-
47	P220/00/50	24.2	2.64	4.386	46	68	93
51	P220/05/50	24.3	2.38	4.425	46	61	93
89	P220/15/50	28.7	2.70	4.444	55	69	94
115	P220/25/50	28.9	2.74	4.425	55	70	93
-	P220/35/50	-	-	-	-	-	-
70	P235/00/50	16.4	2.04	4.367	31	52	92
77	P235/05/50	18.7	1.85	4.376	36	47	92
96	P235/15/50	19.6	2.10	4.255	37	54	90
113	P235/25/50	19.3	1.97	4.348	37	51	92
111	P235/35/50	6.2	0.67	4.274	12	17	90
59	P250/00/50	10.5	1.18	4.202	20	30	89
62	P250/05/50	10.7	1.18	4.160	20	30	88
102	P250/15/50	11.7	1.43	4.098	22	37	86
114	P250/25/50	10.5	1.24	4.115	20	32	87
112	P250/35/50	11.3	1.27	4.032	22	33	85

MIX PROPERTIES - STRENGTH (28 day)

P2/-/50

NO.	MIX CODE	COMP. STRENGTH (N/mm^2)	INDIRECT TENSILE STRENGTH (N/mm^2)	U.S.P.V. (km/sec)	COMP. STRENGTH % 28 DAY CONTROL	INDIRECT TENSILE STRENGTH % 28 DAY CONTROL	U.S.P.V. % 28 DAY CONTROL
C	00/00/50	52.3	3.90	4.739	100	100	100
35	P200/05/50	51.5	3.63	4.686	98	93	99
11	P200/15/50	53.6	4.71	4.695	102	121	99
8	P200/25/50	53.8	4.01	4.748	103	103	100
80	P200/35/50	52.4	3.60	4.662	100	92	98
24	P210/00/50	50.3	3.66	4.695	96	94	99
25	P210/05/50	46.7	3.63	4.651	89	93	98
-	P210/15/50	-	-	-	-	-	-
-	P210/25/50	-	-	-	-	-	-
-	P210/35/50	-	-	-	-	-	-
47	P220/00/50	4.11	3.56	4.651	79	91	98
51	P220/05/50	40.4	3.37	4.630	77	86	98
89	P220/15/50	43.8	3.72	4.566	84	95	96
115	P220/25/50	44.7	3.56	4.587	85	91	97
-	P220/35/50	-	-	-	-	-	-
70	P235/00/50	32.7	2.86	4.525	62	73	95
77	P235/05/50	27.9	2.77	4.535	53	71	96
96	P235/15/50	31.3	2.77	4.444	60	71	94
113	P235/25/50	33.6	3.12	4.485	64	80	95
111	P235/35/50	31.2	2.77	4.454	60	71	94
59	P250/00/50	17.8	1.94	4.464	34	50	94
62	P250/05/50	18.0	1.97	4.405	34	51	93
102	P250/15/50	20.3	2.04	4.338	39	52	92
114	P250/25/50	20.8	2.13	4.329	40	55	91
112	P250/35/50	19.5	1.94	4.237	37	50	89

MIX PROPERTIES - STRENGTH (91 days)

P2/-/50

NO.	MIX CODE	COMP. STRENGTH (N/mm2)	INDIRECT TENSILE STRENGTH (N/mm2)	U.S.P.V. (km/sec)	COMP. STRENGTH % 28 DAY CONTROL	INDIRECT TENSILE STRENGTH % 28 DAY CONTROL	U.S.P.V. % 28 DAY CONTROL
C	00/00/50	60.1	4.11	4.822	115	105	102
35	P200/05/50	62.8	4.29	4.785	120	110	101
11	P200/15/50	64.0	4.39	4.831	122	113	102
8	P200/25/50	64.7	4.46	4.831	124	114	102
80	P200/35/50	66.4	4.23	4.785	127	108	101
24	P210/00/50	56.9	3.82	4.739	109	98	100
25	P210/05/50	55.4	3.98	4.739	106	102	100
-	P210/15/50	-	-	-	-	-	-
-	P210/25/50	-	-	-	-	-	-
-	P210/35/50	-	-	-	-	-	-
47	P220/00/50	47.6	3.69	4.705	91	95	99
51	P220/05/50	50.5	3.72	4.695	97	95	99
89	P220/15/50	56.9	3.95	4.695	109	101	99
115	P220/25/50	54.2	3.98	4.684	104	102	99
-	P220/35/50	-	-	-	-	-	-
70	P235/00/50	40.1	3.37	4.608	77	86	97
77	P235/05/50	40.6	3.25	4.620	78	83	97
96	P235/15/50	44.2	3.53	4.587	84	91	97
113	P235/25/50	43.9	3.72	4.566	84	95	96
111	P235/35/50	44.7	3.53	4.525	85	91	95
59	P250/00/50	25.5	2.61	4.600	49	67	97
62	P250/05/50	25.1	2.55	4.566	48	65	96
102	P250/15/50	30.4	2.90	4.566	58	74	96
114	P250/25/50	27.3	2.48	4.464	52	64	94
112	P250/35/50	29.2	2.96	4.425	56	76	93

MIX PROPERTIES - STRENGTH (7 days)

P1/-/60

NO.	MIX CODE	COMP. STRENGTH (N/mm²)	INDIRECT TENSILE STRENGTH (N/mm²)	U.S.P.V. (km/sec)	COMP. STRENGTH % 28 DAY CONTROL	INDIRECT TENSILE STRENGTH % 28 DAY CONTROL	U.S.P.V. % 28 DAY CONTROL
3	00/00/60	22.6	2.32	4.292	43	59	91
20	P100/05/60	20.0	1.97	4.299	38	51	91
15	P100/15/60	23.7	2.39	4.378	45	61	92
5	P100/25/60	26.4	2.61	4.301	50	67	91
84	P100/35/60	27.0	2.39	4.376	52	61	92
31	P110/00/60	15.8	1.75	4.230	30	45	89
30	P110/05/60	16.3	1.81	4.219	31	46	89
-	P110/15/60	-	-	-	-	-	-
-	P110/25/60	-	-	-	-	-	-
-	P110/35/60	-	-	-	-	-	-
40	P120/00/60	15.6	1.88	4.255	30	48	90
44	P120/05/60	14.2	1.53	4.184	27	39	88
88	P120/15/60	17.9	1.81	4.219	34	46	89
-	P120/25/60	-	-	-	-	-	-
-	P120/35/60	-	-	-	-	-	-
68	P135/00/60	10.0	1.18	3.968	19	30	84
73	P135/05/60	10.3	1.14	4.098	20	29	86
93	P135/15/60	11.0	1.37	4.149	21	35	88
-	P135/25/60	-	-	-	-	-	-
-	"135/35/60	-	-	-	-	-	-
57	P150/00/60	7.1	0.76	3.968	14	19	84
-	P150/05/60	-	-	-	-	-	-
100	P150/15/60	6.2	0.76	3.861	12	19	81
-	P150/25/60	-	-	-	-	-	-
-	P150/35/60	-	-	-	-	-	-

MIX PROPERTIES - STRENGTH (28 days)

P1/-/60

NO.	MIX CODE	COMP. STRENGTH (N/mm^2)	INDIRECT TENSILE STRENGTH (N/mm^2)	U.S.P.V. (km/sec)	COMP. STRENGTH % 28 DAY CONTROL	INDIRECT TENSILE STRENGTH % 28 DAY CONTROL	U.S.P.V. % 28 DAY CONTROL
3	00/00/60	33.5	3.21	4.525	64	82	95
20	P100/05/60	33.4	2.83	4.520	64	73	95
15	P100/15/60	37.5	3.60	4.558	72	92	96
5	P100/25/60	40.1	3.25	4.545	77	83	96
84	P100/35/60	44.7	3.31	4.598	85	85	97
31	P100/00/60	28.6	2.66	4.464	55	68	94
30	P110/05/60	28.0	2.61	4.484	54	67	95
-	P110/15/60	-	-	-	-	-	-
-	P110/25/60	-	-	-	-	-	-
-	P110/35/60	-	-	-	-	-	-
40	P120/00/60	26.4	2.42	4.496	50	62	95
44	P120/05/60	25.2	2.23	4.435	48	57	94
88	P120/15/60	30.2	2.86	4.444	58	73	94
-	P120/25/60	-	-	-	-	-	-
-	P120/35/60	-	-	-	-	-	-
68	P135/00/60	18.9	2.00	4.274	36	51	90
73	P135/05/60	17.2	2.16	4.348	33	55	92
93	P135/15/60	20.7	2.00	4.396	40	51	93
-	P135/25/60	-	-	-	-	-	-
-	P135/35/60	-	-	-	-	-	-
57	P150/00/60	11.9	1.27	4.226	23	32	89
-	P150/05/60	-	-	-	-	-	-
100	P150/15/60	12.7	1.27	4.149	24	33	70
-	P150/25/60	-	-	-	-	-	-
-	P150/35/60	-	-	-	-	-	-

MIX PROPERTIES - STRENGTH (91 days)

P1/-/60

NO.	MIX CODE	COMP. STRENGTH (N/mm2)	INDIRECT TENSILE STRENGTH (N/mm2)	U.S.P.V. (km/sec)	COMP. STRENGTH % 28 DAY CONTROL	INDIRECT TENSILE STRENGTH % 28 DAY CONTROL	U.S.P.V. % 28 DAY CONTROL
3	00/00/60	4.00	3.34	4.651	76	86	98
20	P100/05/60	39.9	3.21	4.600	76	82	97
15	P100/15/60	46.9	3.72	4.695	90	95	99
5	P100/25/60	51.4	4.04	4.545	98	103	96
84	P100/35/60	57.8	4.11	4.695	110	105	99
31	P110/00/60	37.3	2.93	4.608	71	75	97
30	P110/05/60	35.5	2.89	4.608	68	74	97
-	P110/15/60	-	-	-	-	-	-
-	P110/25/60	-	-	-	-	-	-
-	P110/35/60	-	-	-	-	-	-
40	P120/00/60	35.3	2.93	4.619	67	75	97
44	P120/05/60	32.9	2.90	4.630	63	74	98
88	P120/15/60	43.2	3.50	4.577	83	90	97
-	P120/25/60	-	-	-	-	-	-
-	P120/35/60	-	-	-	-	-	-
68	P135/00/60	27.0	2.80	4.359	52	72	92
73	P135/05/60	28.8	2.77	4.515	55	71	95
93	P135/15/60	29.9	1.72	4.515	57	44	95
-	P135/25/60	-	-	-	-	-	-
-	P135/35/60	-	-	-	-	-	-
57	P150/00/60	18.0	1.97	4.398	34	51	93
-	P150/05/60	-	-	-	-	-	-
100	P150/15/60	22.4	2.20	4.444	43	56	94
-	P150/25/60	-	-	-	-	-	-
-	P150/35/60	-	-	-	-	-	-

MIX PROPERTIES - STRENGTH (7 days)

P2/-/60

NO.	MIX CODE	COMP. STRENGTH (N/mm2)	INDIRECT TENSILE STRENGTH (N/mm2)	U.S.P.V. (km/sec)	COMP. STRENGTH % 28 DAY CONTROL	INDIRECT TENSILE STRENGTH % 28 DAY CONTROL	U.S.P.V. % 28 DAY CONTROL
3	00/00/60	22.6	2.32	4.292	43	59	91
34	P200/05/60	23.5	2.45	4.292	45	63	91
12	P200/15/60	23.1	2.26	4.359	44	58	92
9	P200/25/60	22.3	2.32	4.367	43	59	92
81	P200/35/60	27.7	2.61	4.405	53	67	93
-	P210/00/60	-	-	-	-	-	-
32	P210/05/60	18.1	2.00	4.255	35	51	90
-	P210/15/60	-	-	-	-	-	-
-	P210/25/60	-	-	-	-	-	-
-	P210/35/60	-	-	-	-	-	-
48	P220/00/60	13.2	1.46	4.177	25	37	88
50	P220/05/60	14.5	1.72	4.167	28	44	88
90	P220/15/60	16.5	2.10	4.193	32	54	88
-	P220/25/60	-	-	-	-	-	-
-	P220/35/60	-	-	-	-	-	-
69	P235/00/60	10.1	1.11	4.082	19	28	86
78	P235/05/60	9.3	1.05	4.228	18	27	89
99	P235/15/60	9.5	1.08	4.090	18	28	86
-	P235/25/60	-	-	-	-	-	-
-	P235/35/60	-	-	-	-	-	-
58	P250/00/60	5.5	0.60	3.759	11	15	79
63	P250/05/60	5.7	0.64	3.876	11	16	82
103	P250/15/60	6.1	0.70	3.643	12	18	77
-	P250/25/60	-	-	-	-	-	-
-	P250/35/60	-	-	-	-	-	-

P2/-/60

NO.	MIX CODE	COMP. STRENGTH (N/mm2)	INDIRECT TENSILE STRENGTH (N/mm2)	U.S.P.V. (km/sec)	COMP. STRENGTH % 28 DAY CONTROL	INDIRECT TENSILE STRENGTH % 28 DAY CONTROL	U.S.P.V. % 28 DAY CONTROL
3	00/00/60	33.5	3.21	4.525	64	82	95
34	P200/05/60	41.3	3.53	4.525	79	91	95
12	P200/15/60	35.9	3.47	4.566	69	89	96
9	P200/25/60	35.1	3.37	4.570	67	86	96
81	P200/35/60	42.2	3.25	4.566	81	83	96
-	P210/00/60	-	-	-	-	-	-
32	P210/05/60	32.3	2.83	4.484	62	73	95
-	P210/15/60	-	-	-	-	-	-
-	P210/25/60	-	-	-	-	-	-
-	P210/35/60	-	-	-	-	-	-
48	P220/00/60	23.6	2.26	4.476	45	58	94
50	P220/05/60	24.2	2.54	4.464	46	65	94
90	P22015/60	26.1	2.83	4.405	50	73	93
-	P220/25/60	-	-	-	-	-	-
-	P220/35/60	-	-	-	-	-	-
69	P235/00/60	17.6	1.97	4.338	34	51	92
78	P235/05/60	14.8	1.91	4.301	28	49	91
99	P235/15/60	17.3	2.04	4.329	33	52	91
-	P235/25/60	-	-	-	-	-	-
-	P235/35/60	-	-	-	-	-	-
58	P250/00/60	9.6	1.14	4.120	18	29	87
63	P250/05/60	9.4	1.18	4.177	18	30	88
103	P250/15/60	10.3	1.21	4.082	20	31	86
-	P250/25/60	-	-	-	-	-	-
-	P250/35/60	-	-	-	-	-	-

MIX PROPERTIES - STRENGTH (91 days)

P2/-/60

NO.	MIX CODE	COMP. STRENGTH (N/mm2)	INDIRECT TENSILE STRENGTH (N/mm2)	U.S.P.V. (km/sec)	COMP. STRENGTH % 28 DAY CONTROL	INDIRECT TENSILE STRENGTH % 28 DAY CONTROL	U.S.P.V. % 28 DAY CONTROL
3	00/00/60	40.0	3.34	4.651	76	86	98
24	P200/05/60	49.8	4.20	4.640	95	108	98
12	P200/15/60	47.2	3.76	4.643	90	96	98
9	P200/25/60	46.6	3.60	4.695	89	92	99
81	P200/35/60	54.6	3.79	4.651	104	97	98
-	P210/00/60	-	-	-	-	-	-
32	P210/05/60	41.6	3.43	4.608	79	88	97
-	P210/15/60	-	-	-	-	-	-
-	P210/25/60	-	-	-	-	-	-
-	P210/35/60	-	-	-	-	-	-
48	P220/00/60	28.9	2.74	4.598	55	70	97
50	P220/05/60	31.5	2.80	4.619	60	72	97
90	P220/15/60	36.3	3.09	4.515	69	79	95
-	P220/25/60	-	-	-	-	-	-
-	P220/35/60	-	-	-	-	-	-
69	P235/00/60	23.5	2.39	4.474	45	61	94
78	P235/05/60	23.4	2.35	4.425	45	60	93
99	P235/15/60	26.5	3.02	4.525	51	77	95
-	P235/25/60	-	-	-	-	-	-
-	P235/35/60	-	-	-	-	-	-
58	P250/00/60	14.7	1.78	4.367	28	46	92
63	P250/05/60	13.4	1.43	4.398	26	37	93
103	P250/15/60	17.2	1.97	4.348	33	51	92
-	P250/25/60	-	-	-	-	-	-
-	P250/35/60	-	-	-	-	-	-

APPENDIX V

MIX PROPERTIES - DURABILITY

(% weight change after immersion

in 3.5% $MgSO_4$ solution)

MIX PROPERTIES - DURABILITY (Immersion in $MgSO_4$)

CONTROL

NO.	MIX CODE	WT. CHANGE (kg.)	% WT. CHANGE	NO.	MIX CODE	WT. CHANGE (kg.)	% WT. CHANGE
2	00/00/50	+0.032	+1.29				
16	"	-	-				
17	"	-	-				
33	"	+0.007	+0.28				
37	"	+0.012	+0.51				
38	"	+0.010	+0.39				
52	"	+0.023	+0.94				
53	"	+0.018	+0.75				
54	"	+0.022	+0.91				
65	"	+0.013	+0.53				
104	"	+0.017	+0.69				
105	"	+0.032	+1.32				
	Mean		0.761				
	Std. Dev.		0.355				

MIX PROPERTIES - DURABILITY (Immersion in $MgSO_4$)

P1-2/-/40

NO.	MIX CODE	WT. CHANGE (kg.)	% WT. CHANGE	NO.	MIX CODE	WT. CHANGE (kg.)	% WT. CHANGE
1	00/00/40	+0.017	+0.67	1	00/00/40	+0.017	+0.67
18	P100/05/40	-0.020	-0.81	36	P200/05/40	+0.003	+0.13
13	P100/15/40	+0.002	+0.08	10	P200/15/40	+0.015	+0.59
6	P100/25/40	-0.043	-1.73	7	P200/25/40	-0.010	-0.42
-	P100/35/40	-	-	79	P200/35/40	-0.018	-0.83
28	P110/00/40	-0.002	-0.08	26	P210/00/40	-0.004	-0.15
29	P110/05/40	-0.003	-0.11	27	P210/05/40	-0.005	-0.22
-	P110/15/40	-	-	-	P210/15/40	-	-
-	P110/25/40	-	-	-	P210/25/40	-	-
-	P110/35/40	-	-	-	P210/35/40	-	-
41	P120/00/40	-0.009	-0.36	46	P220/00/40	+0.007	+0.28
42	P120/05/40	+0.018	+0.75	49	P220/05/40	+0.019	+0.77
85	P120/15/40	+0.009	+0.39	94	P220/15/40	-0.051	-2.21
-	P120/25/40	-	-	-	P220/25/40	-	-
-	P120/35/40	-	-	-	P220/35/40	-	-
66	P135/00/40	+0.000	+0.01	71	P235/00/40	+0.007	+0.29
75	P135/05/40	-0.001	-0.03	76	P235/05/40	+0.010	+0.42
91	P135/15/40	+0.009	+0.37	95	P235/15/40	-0.000	-0.02
-	P135/25/40	-	-	-	P235/25/40	-	-
-	P135/35/40	-	-	-	P235/35/40	-	-
56	P150/00/40	-0.011	-0.45	60	P250/00/40	-0.002	-0.08
-	P150/05/40	-	-	61	P250/05/40	-0.000	-0.01
97	P150/15/40	-0.053	-2.22	101	P250/15/40	-0.007	-0.29
-	P150/25/40	-	-	-	P250/25/40	-	-
-	P150/35/40	-	-	-	P250/35/40	-	-

P1-2/-/50

NO.	MIX CODE	WT. CHANGE (kg.)	% WT. CHANGE	NO.	MIX CODE	WT. CHANGE (kg.)	% WT. CHANGE
C	00/00/50			C	00/00/50		
19	P100/05/50	+0.009	+0.38	35	P200/05/50	+0.024	+0.97
14	P100/15/50	+0.015	+0.62	11	P200/15/50	+0.010	+0.41
4	P100/25/50	+0.017	+0.48	8	P200/25/50	+0.016	+0.66
83	P100/35/50	-0.000	-0.02	80	P200/35/50	+0.006	+0.27
21	P110/00/50	+0.012	+0.48	24	P210/00/50	+0.017	+0.71
22	P110/05/50	+0.008	+0.32	25	P210/05/50	+0.022	+0.91
-	P110/15/50	-	-	-	P210/15/50	-	-
107	P110/25/50	+0.012	+0.47	-	P210/25/50	-	-
-	P110/35/50	-	-	-	P210/35/50	-	-
39	P120/00/50	+0.014	+0.56	47	P220/00/50	+0.018	+0.73
43	P120/05/50	+0.007	+0.28	51	P220/05/50	+0.019	+0.79
86	P120/15/50	-0.016	-0.68	89	P220/15/50	+0.008	+0.33
116	P120/25/50	+0.013	+0.56	115	P220/25/50	+0.014	+0.61
-	P120/35/50	-	-	-	P220/35/50	-	-
67	P135/00/50	-0.004	-0.18	70	P235/00/50	+0.019	+0.77
74	P135/05/50	+0.005	+0.19	77	P235/05/50	-0.007	-0.29
92	P135/15/50	+0.009	+0.40	96	P235/15/50	+0.002	+0.08
106	P135/25/50	+0.013	+0.54	113	P235/25/50	+0.009	+0.36
109	P135/35/50	+0.006	+0.25	111	P235/35/50	+0.007	+0.32
55	P150/00/50	-0.088	-3.66	59	P250/00/50	-	-
-	P150/05/50	-	-	62	P250/05/50	+0.004	+0.18
98	P150/15/50	+0.002	+0.08	102	P250/15/50	-0.012	-0.53
108	P150/25/50	-0.015	-0.64	114	P250/25/50	-0.000	-0.02
110	P150/35/50	+0.004	+0.17	112	P250/35/50	+0.003	+0.15

P1-2/-/60

NO.	MIX CODE	WT. CHANGE (kg.)	% WT. CHANGE	NO.	MIX CODE	WT. CHANGE (kg.)	% WT. CHANGE
3	00/00/60	+0.001	+0.04	3	00/00/60	+0.001	+0.04
20	P100/05/60	+0.012	+0.50	34	P200/05/60	+0.026	+1.08
15	P100/15/60	+0.008	+0.32	12	P200/15/60	+0.026	+1.11
5	P100/25/60	-0.006	-0.25	9	P200/25/60	+0.025	+1.06
84	P100/35/60	-0.001	-0.04	81	P200/35/60	-0.024	-1.03
31	P110/00/60	-	-	-	P210/00/60	-	-
30	P110/05/60	+0.008	+0.32	32	P210/05/60	+0.030	+1.28
-	P110/15/60	-	-	-	P210/15/60	-	-
-	P110/25/60	-	-	-	P210/25/60	-	-
-	P110/35/60	-	-	-	P210/35/60	-	-
40	P120/00/60	+0.018	+0.77	48	P220/00/60	+0.001	+0.03
44	P120/05/60	+0.003	+0.13	50	P220/05/60	+0.021	+0.89
88	P120/15/60	+0.008	+0.36	90	P220/15/60	+0.014	+0.60
-	P120/25/60	-	-	-	P220/25/60	-	-
-	P120/35/60	-	-	-	P220/35/60	-	-
68	P135/00/60	+0.023	+1.24	69	P235/00/60	-0.008	-0.02
73	P135/05/60	+0.018	+0.78	78	P235/05/60	+0.009	+0.40
93	P135/15/60	+0.020	+0.82	99	P235/15/60	+0.009	+0.38
-	P135/25/60	-	-	-	P235/25/60	-	-
-	P135/35/60	-	-	-	P235/35/60	-	-
57	P150/00/60	-0.200	-8.53	58	P250/00/60	+0.010	+0.44
-	P150/05/60	-	-	63	P250/05/60	-0.006	-0.27
100	P150/15/60	-0.179	-7.59	103	P250/15/60	-0.034	-1.50
-	P150/25/60	-	-	-	P250/25/60	-	-
-	P150/35/60	-	-	-	P250/35/60	-	-

LIST OF ABBREVIATIONS

Organisations

A.S.T.M.	–	American Society of Testing and Materials.
B.C.U.C.	–	British Coal Utilisation Council.
B.P.R.	–	Bureau of Public Roads (U.S.A.)
B.S.I.	–	British Standards Institution.
B.R.E.	–	Building Research Establishment.
C. & C.A.	–	Cement and Concrete Association.
C.E.G.B.	–	Central Electricity Generating Board.
C.E.R.I.L.H.	–	Centre d'Etudes et des Recherche de l'Industrie des Liants Hydrauliques
R.I.L.E.M.	–	Reunion Internationale des Laboratoires d'Essai et de Recherches sur les Materiaux et les Constructions.

Miscellaneous Terms

C.R.	-	Cement replacement.
C.S. (F_C)	-	Compressive Strength.
C.F. (C_F)	-	Compacting Factor.
F.A.R.	-	Fine aggregate replacement.
O.P.C.	-	Ordinary Portland Cement.
P.F.A. (p.f.a.)	-	Pulverised fuel ash.
P.1 (Pozz. 1)	-	Pozzolan 1 (selected p.f.a.)
P.2 (Pozz. 2)	-	Pozzolan 2 (unselected p.f.a.)
s.	-	estimated population standard deviation from sample.
S_L	-	Slump (mm)
U.S.P.V. (V)	-	Ultra-sonic pulse velocity.
V_B	-	VeBe time (secs)
$\bar{x}$	-	sample mean.