The ultimate aims of this paper are to investigate the response of a prestressed concrete pavement slab to an applied load, and to determine the manner by which the slab fails.

Towards these ends, the modes by which materials in general react to load has been studied; and critical strain in tension, or in shear, as applicable, has been suggested as the criterion for predicting failure.

The next step leading to the achievement of the aims is to study the behaviour of concrete under the application of an external load.

PART 3

THE MECHANICAL BEHAVIOUR OF CONCRETE UNDER LOAD
3. THE MECHANICAL BEHAVIOUR OF CONCRETE UNDER LOAD.

3.1 Observation On The Nature Of Concrete

Constituents & Rheological Behaviour

3.1.1

i) Concrete is composed of a graded granular mass rigidly bound by a hydrated cement matrix. The cement hydrates, in a time-dependent chemical reaction, to form a gel which is crystalline in character, though the grains are exceedingly fine.

ii) The cement paste is really viscoelastic in nature: and if the concrete contains an excess of paste, the properties of the concrete are affected accordingly. Strictly speaking, therefore, a study of the rheological properties of the concrete should also be made, especially if the time-dependent effects such as creep are to be examined.

However, concrete exhibits a near-elastic behaviour if the time intervals between observations are short enough. Since this paper deals with the effects of loads which are applied through a comparatively short period of time, the time-dependent properties of concrete are not of significance. This study of concrete will therefore be confined to its near-elastic properties only.
The Roles Of The Constituents

3.1.2

i) Some authorities have made the observation (33) that the strength of concrete depends only on the matrix. This is not considered a valid observation. The strength of concrete depends on both, the aggregates and the matrix, and both are equally important, with this distinction: in a well-designed, properly compacted mix, most of the external load should be taken by the aggregate; in a poorly-designed mix, most of the load is taken by the matrix.

ii) Stone has a very high strength in compression as compared to the cement binder. It therefore behaves the designer to make as much use as possible of this high strength which is available. The strength of the stone pieces could be utilised in the optimum way if each piece could be shaped and fitted together in the manner of a giant, three-dimensional jig-saw puzzle. In this case a binder would not be necessary. Since this is not practicable, the next best solution would be to rod and compact the stone pieces so that they bear closely against each other, and then to fill the interstices with a binder. The mechanical functions of the binder would be: a) to provide a hydrostatic confining effect to the granular mass so as to prevent slip; b) to mobilise the
friction that develops between the aggregate pieces; c) to mobilise friction and cohesion between the aggregate and the binder itself (which constitutes the bond); d) to increase the bearing between the stone particles.

It is therefore seen that in a well-designed, properly compacted concrete mass, the relevant mechanical characteristics of the stone (which are shape, size, grading, texture and strength) are utilised to the best advantage. Interlocking, bearing and friction between aggregates are properly mobilised. The mass interacts as a whole, with the stone particles functioning as a skeleton. The stone absorbs the major portion of the load as it is transmitted through the mass, in accordance with the principles established in subsection 2.5.4.2, and the binder is required to carry only the lesser components.

It is to be observed that even if the concrete mass is stressed in tension, the hydrostatic confining effect exerted by the binder on the aggregate mobilises friction and interlocking between the stone pieces, and allows some part of the load to be taken by the stone in tension.
iii) It will be appreciated that if the quantity of the binder is too little, voids will be left in the concrete. If the quantity of the binder is too much, the stone particles will move apart by that amount, and so provide less interlocking and friction between themselves. (Hence the observation that 'a concrete vibrator, if used long enough to compact the concrete thoroughly, will design its own mix').

iv) It will also be appreciated that when the aggregates are packed to form a compact mass, the binder not yet being added, there is an optimum volume of voids which should be extant in the aggregate mass. The criterion is not that the aggregates must have minimum voids; because, considering that it is not possible to shape the stone particles into close-fitting, interlocking pieces (which is the only condition under which voids need not be extant), there must obviously be space in the mass in which to place an adequate quantity of binder. The optimum value for the volume of voids depends on the type of aggregate.

v) This concept of optimum voids in Mixed Aggregates (VMA) is borrowed from bituminous mix design. The author is developing a method of designing concrete mixes based on the VMA criterion. However, the question
of the design of mixes (or of the testing of aggregates and the testing of fresh concrete) has no place in this paper.

vi) It has been stated by many authorities that using the maximum size of aggregate, commensurate with the job, will yield concretes of higher strengths. It has also been shown in this paper, subsection 2.4.2 xiii, that smaller sized particles contribute to higher strengths in materials. This seeming paradox is resolved thus:

One of the functions of the water that is used in concrete, (apart from it being required for the chemical hydration of the cement), is to lubricate the aggregates so as to achieve good compaction. Any excess water, however, serves to weaken the hydrating matrix. Lubricating water must therefore be kept to a minimum. Large-sized aggregates have less surface area, for a given volume, than have small-sized aggregates, and therefore require less lubricating water to achieve the same compaction. For the same compaction therefore, the matrices associated with the larger sized aggregates will have a greater strength. A compromise has thus to be effected between size of aggregate and the quantity

Th. 2279
of water required for lubrication. Other things being equal, of course, (eg- compaction), smaller sized aggregates must provide concretes of higher strengths.

3.2 Observations On Mechanical Behaviour

Behaviour At The Microscopic Level

3.2.1

i) Concrete is a heterogeneous material. As a consequence, the 'routes' along which an externally applied load can be transmitted through the mass may be described as follows:

a) through the mass of each aggregate piece
b) through the bearing surfaces between aggregates
c) through the friction surfaces between aggregates
d) through the interlocking portions of aggregates
e) through the aggregate/binder interface (bond, cohesion)
f) through the binder.

ii) The type, direction and level of induced stress at any point will therefore depend on the manner in which the transmitted force is routed and resolved into components by the time it reaches that point.
iii) Failure may therefore occur in any one of more of the transmitting mediums. Failure at any particulars medium can, of course, occur only in tension or shear. To analyse such failures would require the work to be done at the microscopic level. Attempts have been made to do so, as by assuming a simulated 'crystalline structure' to define concrete. The difficulties of such analyses are enormous.

iv) Under most conditions of loading, however, the loadprint is very much larger in size than the largest single constituent of the concrete, which constituent is the coarse aggregate. Moreover, the constituents are oriented throughout the mass in a completely random pattern. As a result, and for all practical purposes at the engineering level, concrete can be assumed to be homogeneous, and isotropic to all mechanical properties. This macroscopic transformation makes analysis very much easier than if it had to be carried out at the microscopic level.

**Behaviour At The Macroscopic Level**

3.2.2

1) Concrete is not truly elastic at any stress level. This is probably because microcracks occur almost from the time that hydration starts, due to shrinkage.
Slight cracking also occurs at about 25-35% of the ultimate load (2), but this is probably due to insignificant 'adjustments' in bond. Appreciable internal cracking occurs at about 75% of the ultimate load.

ii) Concrete does not show a linear strain response to stress. This follows from the interparticle force-spacing relationship as illustrated in Fig 5, and would be accentuated by the early development of cracks as just noted.

iii) Concrete is brittle, and exhibits comparatively little deformation before failure.

iv) In the nature of its manufacture, concrete is rich in flaws, which occur at random. The strengths at failure will therefore vary from specimen to specimen.

v) Tests show that shear failure is brought about by a rupture of the interparticle bonds. The mode of failure in shear is therefore that of shear fracture. (see subsection 2.5.3.7 a Si No 21, Table T-2) It is probable that shear failure is triggered by tension failure across inclined planes.

vi) The modulus of elasticity varies from load to load. This follows from the interparticle force-spacing relationship as illustrated in Fig 5 and would be accentuated by the early development of cracks.
3.3. Observations On the Evaluation Of The Engineering Properties Of Concrete

Engineering Properties To Be Evaluated

3.3.1

1) As has already been noted while considering materials in general (see subsection 2.6-1), the more important engineering properties of concrete that should be ascertained (apart from time-dependent & impact properties) are:

a) the stress-strain response under uniaxial tensile/compressive loads, along the line of action of the loads and in the transverse direction.

b) the stress-strain response along the line of action of a shearing load.

c) the critical strain at failure in tensile fracture.

d) the critical strain at failure in shear fracture.

These will give K, G, E, U and the critical strains, (and consequently the critical stresses, though these are unimportant, since it is better to work from critical strains).
ii) Contrary to current practice which emphasises the compression test, it is considered that the tensile and shear characteristics of concrete are of far greater importance. Concrete is acknowledged to be 'weak in tension'; and in any case, as has already been demonstrated, a material can fail in only tension or shear. Moreover, the tension characteristics are being used frequently in analysis, though somewhat unconsciously. Thus, to cite an example, the analysis of concrete pavement slabs is based on the flexural tensile strength of concrete.

**Discussion On the Conventional Tests**

3.3.2

1. **Conventional Tests On Concrete**

   The tests usually performed on concrete are:

   i) the cube test, to obtain the 'compressive strength'

   ii) the cylinder test (height=2xdia.), to obtain the 'compressive strength'

   iii) the flexure test, to obtain E and the modulus of rupture

   iv) the ultrasonic test/resonant vibration test, to obtain E and U

   v) the prism test, (height=2xlateral dimension) to obtain E and the 'compressive strength'.
2 Comments on The Conventional Tests

i) As has been noted elsewhere in this paper, the term 'compressive strength of concrete' has no meaning. (subsections 2.5.1 - 2.5.3 - 55) What is really being evaluated by the relevant tests is the strength, under a uniaxial compressive load, of that particular shape of specimen.

ii) If no friction were to develop between the surfaces of a compression test specimen and the platens of the compression testing machine, the specimen would expand uniformly in the lateral direction, throughout its height, while it contracted axially under the compressive load. (Fig 8) It would be observed that, owing to the tensile strain that develops in the lateral direction, there is every chance of failure occurring by tensile fracture at the periphery due to the tensile strain there becoming critical. This would lead to vertical cracks occurring on the periphery of the specimen.

Such cracks have been observed, with cubes and more especially with cylinders, in tests where friction at the concrete-platen interface has been reduced. (See Sl No 13 of Table T-2).

Some of the investigators who have observed the same effect have opined that the vertical cracking has
been due to concentrations of stress developing through uneven friction-reducing layers. The author disagrees, in that the vertical cracking always starts at the periphery. If the cracks were due to uneven loading, they should also start at random points from within the interface area.

Cylinders show fairly obvious vertical cracking. In the case of cubes and prisms, however, the vertical edges effect a restraint over the development of the vertical cracks. It is considered that the 'resultant' crack would therefore take an inclined form, much in the manner of the cracks commonly attributed to shear. (Fig 8)

What has been described just now does not, of course, preclude tensile and shear fracture from occurring elsewhere where strains may be becoming critical.

iii) When friction develops at the specimen-platen interface, it acts as an external centripetal force over the surface of the specimen. It thus restrains, or binds, the material there (thus 'strengthening' the concrete at the ends); and its effects travel from the ends towards the middle portions of the height of specimen, diminishing progressively. As a result, a bulge develops in the central portions of the specimen,
in contradistinction to the even lateral expansion of the friction-free specimen. (See S.No 12 of Table T-2; Photograph No 134; & Fig 8)

Due to the end friction restraint, and in conjunction with the vertical compression, a triaxial state of stress is applied over those portions of the specimen to which the effects of the frictional restraint extend. A cube has a height: lateral dimension ratio of only 1, and as a result the end friction restraint effects are felt throughout the height of the cube. The cube is therefore under a complicated system of applied triaxial stress; and a cube test is anything but the 'simple' test it is made out to be. It should not be used.

iv) The effects of the end friction restraint become negligible at a distance from the ends equal to about the lateral dimension. A specimen whose height: lateral dimension ratio is over 2, can therefore be deemed to be free from applied triaxial stress at the mid-sections. The height cannot be increased much over this figure, however, or buckling would tend to occur. Prisms and cylinders with a height: lateral dimension ratio of 2 to 2.5 should therefore be tested in preference to cubes.
v) The flexure test, as has been previously noted, provides, inter alia, an efficient means of obtaining the flexural tensile strain (and flexural tensile stress) at failure in flexure. It is suggested that flexural tensile strain is a particularly useful tool to use while investigating failure in pavement slabs. It is easier to apply than is the concept of critical stress.

vi) Ultrasonic and resonance tests provide convenient means of establishing $E$ and $U$ accurately. However, they can give no direct information regarding the strength of concrete.
Supplementary Tests That Are Advocated

3.3.3

The following tests would also help to provide useful information on the properties of concrete:

i) tensile split test
ii) triaxial test
iii) hydrostatic compression test
iv) hydrostatic tension test (possibly using hollow cylinders).
v) Torsion test
vi) impact test

The characteristics and advantages of these tests have already been described. (see section 2.6)