EFFECT OF SOME FACTORS ON THE MODULUS OF ELASTICITY AND MODULUS OF DEFORMABILITY OF LIGHTWEIGHT CONCRETE

T.G.Abadjieva
Department of Civil Engineering
Faculty of Engineering and Technology
University of Botswana
Gaborone, Botswana

Investigations of the influence of various factors on the modulus of elasticity and deformability of different types of lightweight concrete are presented. The results show that the moduli are not constant and decrease with the increase of the level of applied stress. Aggregate porosity and volume fraction affect the modulus of elasticity and the modulus of deformability of concrete. Using different concrete mixes of varying strength, it was confirmed that the modulus of elasticity and the compressive strength of concrete are not directly proportional. The modulus of elasticity per unit strength decreases with the age of concrete. As lightweight concrete is a heterogeneous, multiphase material, the volume fraction and modulus of elasticity of the principal constituents influence the modulus of elasticity of the composite material.

1. INTRODUCTION

The elastic characteristics of a material are measures of its stiffness. The slope of the relationship between stress and strain under uniaxial loading is defined as modulus of elasticity. Determination of the elastic modulus of concrete is necessary for stress analysis associated with environmental effects and for computing of the design stresses, deformations and deflections under load in concrete and reinforced concrete structures.

Concrete is a composite, multiphase, elasto-plastic material. Its behaviour under loading depends on the properties of the individual phases. The stress-strain diagram is described as non-linear and non-elastic. When stress is applied to concrete, the observed strain is made up of two parts: an elastic deformation, which can recover after removal of the loading and a permanent residual plastic deformation. The explanation for this behaviour lies in the contribution of microcracking to the overall concrete strain.

The non-linearity of the stress-strain relationship means that a number of different elastic modulus values can be defined depending on the particular definition adopted [1-4].

- The term *Young's modulus* is only applicable to the initial straight portion of the curve. In fact, even this part is slightly curved, and the slope of the line, tangent to the curve at the origin, in the case of concrete, is called *initial tangent modulus.* The *dynamic modulus of elasticity* is determined using sonic methods and corresponds to a very small instantaneous strain. The value obtained is unaffected by creep and is approximately equal to the initial tangent modulus.

- The slope of the tangent at any point of the stress-strain curve is the *tangent modulus* of concrete at that point.

- The slope of the line between two arbitrary points on the curve is known as the *chord modulus.*

- The slope of the line joining any arbitrary point on the curve to the origin is known as the *secant* or *static modulus* of concrete. The determination of the secant modulus is of greatest importance in common structural design.

For the determination of the value of the modulus of elasticity, different methods are developed (for example, BS 1881: Part 121, ASTM C469). As the most common measure of the stiffness of the material, the secant modulus is adopted and is usually measured at stresses ranging from 15 to 50 per cent of the short-term strength [2,6,7].

In normal weight concrete the formation and propagation of microcracks results from the incompatibility of the stiffness of the aggregate and the matrix (cement-mortar components). This has been recognized as the cause of fracture and failure of concrete and the non-linearity of the stress-strain curves. According to Young, Midness and Bentur [4] and Clarke [5], the process of fracture and failure starts with progressive development of stable microcracks (bond cracks) at the contact zone at stresses of about 25-50 % of the ultimate stress. This is followed by stable and than unstable fracture propagation (from approximately 75 to 85 % of ultimate stress).

In lightweight concrete, greater compatibility exists between the stiffness of lightweight aggregates and the surrounding cementous matrix. For this reason according to Clark [5], the stable fracture initiation stage is extended and the unstable fracture propagation stage is reduced. As a result, complete disruption occurs suddenly at ultimate stress and the stress-strain curves tend to be more linear.

In the present paper, the author has made an attempt to investigate the influence of various factors on the modulus of elasticity and modulus of deformability of different types of lightweight concrete.

2. MATERIALS AND METHOD OF TESTING

Laboratory tests were conducted using concrete mixes with different types of aggregates:

- Mix No 1 - normal weight concrete with normal weight aggregates - river sand and crushed stone with maximum size 10 mm, (density 2400 kg/m^3);
- Mix No 2 - lightweight concrete with lightweight fine and coarse aggregates - expanded clay, with plasticiser - air entraining agent, (density 1300 kg/m^3);
- Mix No 3 - lightweight concrete with lightweight fine and coarse aggregates - expanded clay and perlite, with plasticiser, (density 800 kg/m^3);
- Mix No 4 - lightweight concrete with lightweight fine and coarse aggregates - expanded clay and perlite, without plasticiser, (density 900 kg/m^3).

For each mix concrete prisms 100 x 100 x 400 mm were prepared and the ultimate prism strength in compression $f_{c,p}$ was estimated. The higher slenderness of the prisms was necessary for the installation of compressometers and this can reduce slightly the strength results.

In the investigations a static test for determination of the modulus of elasticity and the modulus of deformability of concrete was used [6,7]. The concrete prisms were loaded in longitudinal compression at a constant loading rate. The corresponding strain was measured using compressometers. Initially the concrete prisms were loaded with a load, which causes compressive stress equal to 5 per cent of the ultimate compressive strength ($\sigma/f_{c,p} = 0.05$). On the second minute from the beginning, the readings from the compressometers were recorded. The loading continued until stress of $0.1f_{c,p}$ and $0.2f_{c,p}$ was reached and the deformations recorded. The sample was than unloaded to $0.05f_{c,p}$ and the value of the elastic deformation ε_e was determined. The successive unloading/loading cycles continued at $0.1f_{c,p}$ intervals up to the stress level $0,6f_{c,p}$. At each load level readings on compressometers were taken. Repeated loading and unloading reduces the subsequent creep [3]. The stress-strain curve on third or fourth loading exhibits only small curvature. Measuring strain for very small variations of stress also largely eliminates creep.

The relative total deformations $\Delta\varepsilon_d$ and the relative elastic deformations $\Delta\varepsilon_e$ were determined using the following formulae:

$$\Delta\varepsilon_d = (a_{l,i} - a_{l,0})/\, l_0$$
$$\Delta\,\varepsilon_e = (a_{l,i} - a_{ul,i})/\, l_0,$$

where al,i is the reading at the end of the loading;
$a_{ul,i}$ is the reading at the end of the unloading;
$a_{l,0}$ is the reading at stress $0.05f_{c,p}$;
l_0 is the gauge length = 100 mm.

The modulus of elasticity (E_e) corresponding to elastic deformations ε_e and modulus of deformability (E_d) corresponding to total deformations ε_d (elastic and plastic) were calculated using the following formulae:

$$E_e = \Delta\sigma/\Delta\varepsilon_e$$
$$E_d = \Delta\sigma/\,\Delta\varepsilon_d,$$

where $\Delta\sigma$ is the increase of the stress.

The modulus of elasticity and the modulus of deformability depend on the level of applied stress chosen (expressed as a percentage of the ultimate load). In calculations of the modulus of elasticity and modulus of deformability, the point on the curve corresponding to 30 per cent of the failure load was used.

3. FACTORS INFLUENCING THE MODULUS OF ELASTICITY AND MODULUS OF DEFORMABILITY OF CONCRETE

3.1 Magnitude of the applied stress and age of concrete

Fig. 1 shows the influence of the stress level on the modulus of elasticity E_e and the modulus of deformability E_d of normal weight concrete (mix No 1) at different ages - 4 and 18 days. The stress level is expressed as the ratio of the existing stress in concrete σ to the ultimate compressive prism strength of the specimen $f_{c,p}$.

It can be seen from the graph, that both moduli decrease with an increase in the level of the applied stress and the age of concrete. At the age of 4 days with the increase of level of loading from $0.1f_{c,p}$ to $0.95f_{c,p}$ the modulus of elasticity decreases 3,18 times and the modulus of deformability - 4.16 times.

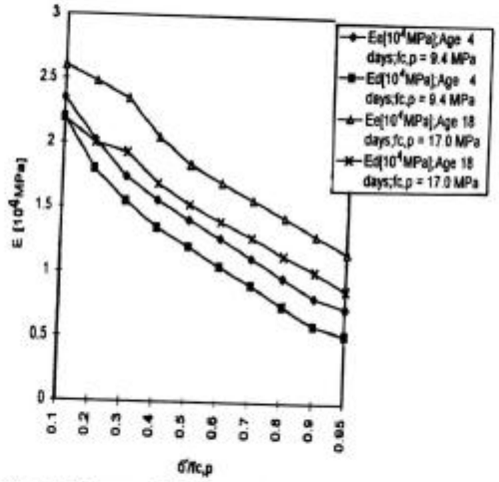

Fig. 1 Influence of the level of applied stress $\sigma/f_{c,p}$ on the modulus of elasticity of concrete E_e and modulus of deformability E_d of concrete for normal weight concrete grade 20, d_{max} = 10mm

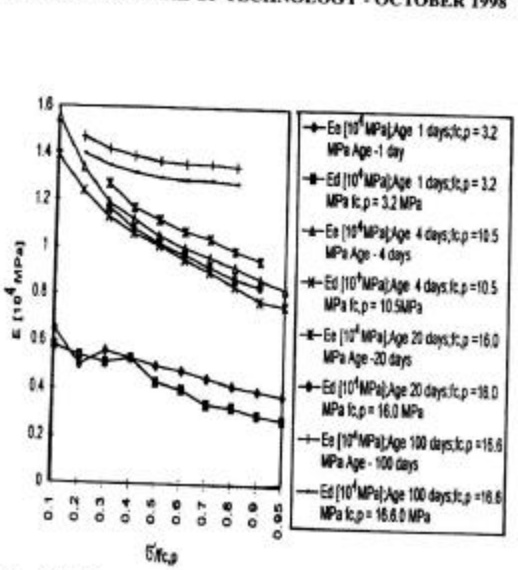

Fig. 2 Influence of the level of applied stress $\sigma/f_{c,p}$ on the modulus of elasticity of concrete E_e and modulus of deformability E_d of lightweight concrete with lightweight aggregates - expanded clay; mix No 2

At the age of 18 days with the increase of level of loading from $0.25f_{c,p}$ to $0.95f_{c,p}$ the modulus of elasticity decreases 2.15 times and the modulus of deformability - 2.36 times. These results confirm the fact, that modulus of elasticity of concrete decreases if the stress at which it was determined is increased. The increase in strain while the load is acting is due to the creep effect in concrete, which is more at higher stress [6,8].

The difference between modulus of elasticity and modulus of deformability is greater at higher levels of loading. The reason for this is the increased portion of plastic deformations in total deformations and the higher creep at earlier age of loading. Both moduli increase with the increase in age of concrete.

3.2 Porosity of aggregates

In addition to the level of loading, the most important characteristic that influences the modulus of elasticity of concrete is porosity of aggregates. This is because the porosity determines the stiffness and the ability of the aggregate to restrain matrix strains. The much lower elastic modulus of porous lightweight aggregates has a strong influence on the modulus of elasticity of concrete.

Fig. 2 shows the influence of the stress level $\sigma/f_{c,p}$ on the modulus of elasticity E_e and the modulus of deformability E_d of concrete at different ages - 1, 2, 4 and 100 days. Lightweight concrete with lightweight aggregates - expanded clay (mix No 2) was used.

It can be seen that the curves follow the same tendency of decrease of the moduli with the increase of the level of stress as for normal weight concrete. Here the moduli of elasticity and deformability decrease from 1,09 to 1.76 times over the range of loading stresses from $0.15f_{c,p}$ to $0.95f_{c,p}$ depending on the age of concrete. The decrease is less significant after the age of 100 days because of the completed hydration process, improved aggregate-matrix bond and higher density of concrete.

The influence of the level of stress $\sigma/f_{c,p}$ on the modulus of elasticity E_e and the modulus of deformability E_d of concrete at different ages - 5, 15 and 32 days is shown in Fig. 3. The results are for lightweight concrete with lightweight aggregates - expanded clay and perlite (mix No 3). The use of air-entraining agent in the mix improves the workability, reduces the tendency to bleeding and segregation, decreases the water requirements, cement content and strength of lightweight concrete. The same tendency of decrease in moduli could be observed - the decrease in moduli here is from 2.53 to 3.95 with the increase in the level of stress on loading from $0.2f_{c,p}$ to $0.95f_{c,p}$.

Fig. 4 represents the influence of the level of the applied stress $\sigma/f_{c,p}$ on the modulus of elasticity E_e and the modulus of deformability E_d of concrete at different ages - 5, 9, and 19 days. Lightweight aggregates - expanded clay and perlite, without plasticiser (mix No 4) were used. In this case, the decrease in moduli is between 1.36 and 2.4 times

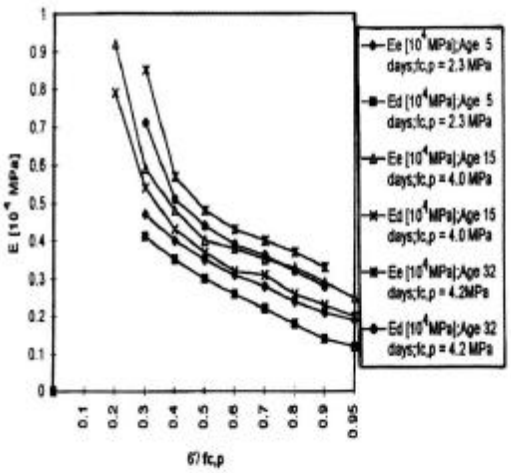

Fig. 3 Influence of the level of applied stress $\sigma/f_{c,p}$ on the modulus of elasticity of concrete E_e and modulus of deformability E_d of lightweight concrete with lightweight aggregates - expanded clay (as a coarse aggregate and perlite as fine aggregate) and plasticiser; mix No 3.

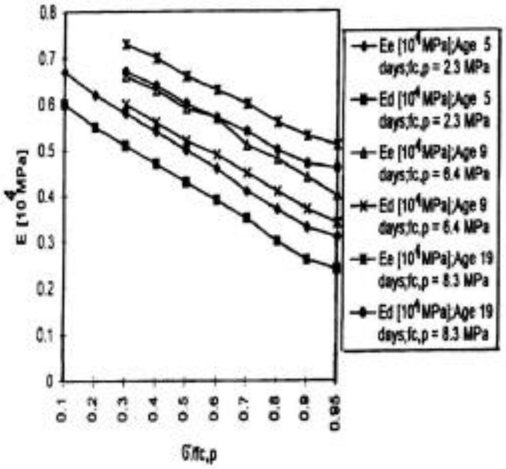

Fig. 4 Influence of the level of applied stress $\sigma/f_{c,p}$ on the modulus of elasticity of concrete E_e and modulus of deformability E_d of lightweight concrete with lightweight aggregates - expanded clay (as a coarse aggregate and perlite as fine aggregate) without plasticiser, mix No 4.

over the range of loading from $0.1f_{c,p}$ to $0.95f_{c,p}$. A comparison between Fig. 3 and Fig. 4 shows that the change of moduli with the increase of the level of applied stress is less for mix No 4 than for mix No 3.

Generally, the modulus of elasticity of lightweight concrete is usually between 30 and 60 per cent of the modulus of normal weight concrete of the same strength. The lower the modulus of elasticity of the aggregate the lower the modulus of the resulting concrete.

Modulus of elasticity of concrete is always 20-30 per cent higher than the corresponding modulus of deformability because elastic deformations are always less than total.

3.3 Strength and age of concrete

The investigations have confirmed that the curing age influences the modulus of elasticity and the strength of concrete but no to the same degree.

The calculated ratio $E/f_{c,p,28}$ (Fig. 5) shows that the modulus per unit strength decreases with time. The decrease is greater for the earlier ages of concrete. The downward tendency of the E - $f_{c,p}$ curve confirms that the modulus of elasticity and strength correlate, but not directly. At later ages, strength increases more rapidly than the modulus of elasticity of concrete.

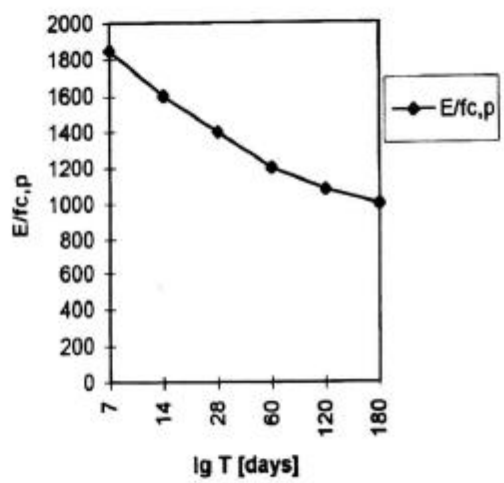

Fig. 5 Variation of modulus of elasticity per unit strength $E/f_{c,p}$ with the time for normal weight concrete grade 20.

Fig.6 shows the results from the investigations of strength and modulus of elasticity of concrete with different types of aggregate (normal weight, expanded clay, shale, slate, and perlite). It can be seen from the figure that the modulus of elasticity is greater the stronger and denser the concrete is.

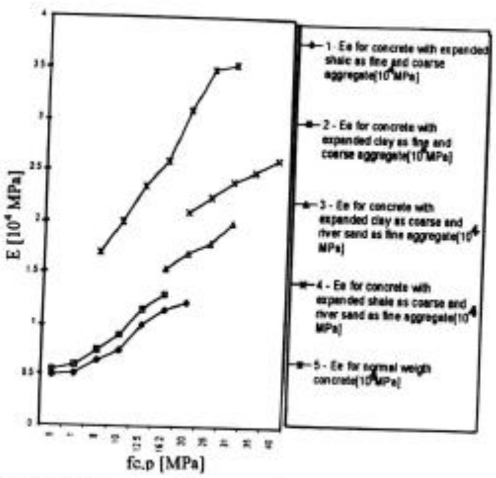

Fig. 6 Influence of the type of aggregate and the strength of concrete $f_{c,p}$ on the modulus of elasticity of concrete

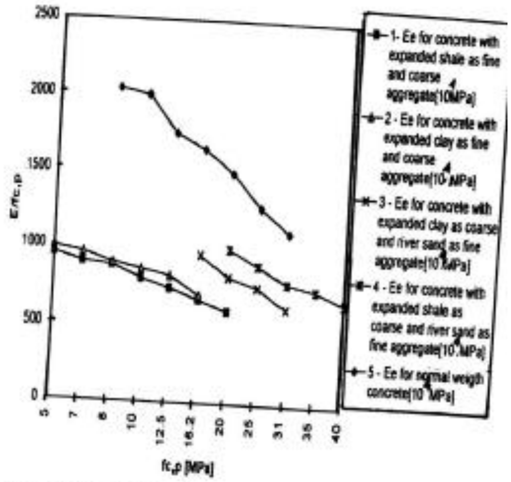

Fig. 7 Correlation between modulus of elasticity per unit strength $E/f_{c,p}$ and strength $f_{c,p}$ of concrete made with different types of aggregates

The variations in the modulus of elasticity of concrete per unit strength with the increase in the strength are given in Fig. 7. The character of the curves has shown again that the modulus of elasticity influences the strength of concrete but not directly. The relation between modulus of elasticity and strength, according to A.M.Neville [3] depends also on the mix proportions (since aggregate generally has a higher modulus than the cement paste).

3.4 Analysis of the contribution of components of lightweight concrete on the modulus of elasticity

As concrete is a composite material, comprised of a matrix (cement-sand mortar) and coarse aggregate, the homogeneous strain model developed by Voigt might be used to describe the influence of the components of the dispersed system on its modulus of elasticity. A modified simple formula for determination of the modulus of elasticity of a composite using the rule of mixture [4] is given below:

$$E = C_1 \xi E_m + C_2 \eta E_{ca}$$

where C_1 is a coefficient which takes into account the change of the modulus in elasticity or the modulus of deformability of the mortar in the given disperse system;

ξ is the volume fraction of the matrix (mortar);

E_m is the elastic modulus of the mortar;

C_2 is a coefficient, which takes to account the change in the modulus of elasticity or the modulus of deformability of the aggregates in the given disperse system;

η is the volume fraction of the course aggregate;

E_{ca} is the elastic modulus of coarse aggregate.

This formula gives the possibility to explain the following:

- in the case of normal-weight concrete with normal-weight aggregates the modulus of aggregates is much higher than the modulus of elasticity of the mortar. That is why concrete with larger maximum aggregate size has a higher modulus of elasticity (void fraction effect);
- in the case of lightweight concrete with normal weight river sand and lightweight aggregates, the modulus of elasticity increases with the increase of the volume fraction of the mortar under equal other conditions;
- in the case of the lightweight concrete with lightweight fine and coarse aggregates, the modulus of elasticity is proportional to the volume fraction of the coarse aggregate.

4. CONCLUSIONS

The level of loading has the same effect on the modulus of elasticity and the modulus of deformability of lightweight concrete as for normal weight concrete. The moduli decrease with the increase of level of applied stress. The extent of the decrease depends on the type of concrete (porosity of aggregates), the level of stress under loading and the age of concrete.

The type and the amount of aggregates have a substantial influence on the modulus of elasticity and the modulus of deformability of concrete. The higher the amount of lightweight aggregates with lower density in the concrete mixture, the lower the modulus of elasticity and the modulus of deformability of concrete.

The increase in modulus of elasticity and modulus of deformability with time is proportional to the strength but the increase in the modulus is less than the increase of strength with time. The ratio $E/f_{c,p}$ (modulus per unit strength) decreases with an increase in the strength of concrete.

Referring to lightweight concrete as a two-phase material and using the rule of mixes, a simple formula for estimation of the modulus of elasticity of the composite product was considered. The modulus of elasticity of lightweight concrete depends on the value of the modulus of elasticity of the mortar and the aggregate, and on their volumetric proportions.

5. REFERENCES

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