CREEP CHARACTERISTICS OF CONCRETE MADE OF BRICK CHIPS IN BANGLADESHI ENVIRONMENT

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By

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TO MY PARENTS

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DECLARATION

I do hereby declare that the research work on '*Creep characteristics of concrete made of brick chips in Bangladeshi environment*' under the supervision of Dr. Syed Ishtiaq Ahmad, Professor, Department of Civil Engineering, BUET, reported in this thesis has been performed by me and that this work has not been submitted elsewhere for any other purpose, except for publication.

MARCH, 2012

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ABSTRACT

To study the effect of brick chips as coarse aggregate on creep behavior of concrete, a comprehensive testing program is conducted at Bangladesh University of Engineering & Technology, Dhaka, Bangladesh. Concrete cylinder specimens having compressive strength of 17.2, 24.0 and 27.5 MPa are prepared from both natural stone and crushed clay brick aggregate. Mix design ratios are evaluated in a way so that volumetric content of coarse aggregate (both brick and stone) remain approximately same for all concrete samples. Specimens are then subjected to creep testing at 7th and 28th day after casting and creep strain data are recorded up to 300 days. Results show that although strength and other environmental parameters remain same, concrete made from crushed clay brick as coarse aggregate have higher creep strain than that of concrete made from natural stone aggregate. This increase in creep strain ranges from 30% to as high as 45% for the 300 day loading history considered.

Additionally, in order to select an appropriate model to predict creep in brick aggregate concrete, effectiveness of five widely used prediction models are examined. For this, predicted creep strain from ACI 209, CEB-FIP 90, B3, GL 2000 and Euro code 2 models are compared with experimental results. Using statistical analysis, it is established that prediction of creep by GL2000 model is closest to the experimental result. A modification factor is then proposed which may be incorporated so that prediction of creep strains by GL 2000 model for brick aggregate concrete becomes more realistic.

Furthermore, a simple design oriented empirical model containing only two parameters has been developed to predict creep behavior of concrete made of crushed clay bricks as coarse aggregate for a stress/strength ratio of 0.35. For each concrete strength category, using the available test result a hyperbolic equation is developed from their creep-time behavior. These equations are then combined and modified according to statistical norms to finally obtain a generalized equation. Comparison of creep strain obtained from this equation with that of experimental values show that the proposed model can closely predict creep in brick aggregate made concrete.

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CHAPTER 1

INTRODUCTION

1.1 GENERAL

Concrete is the main ingredient and most commonly used building materials for the construction industries throughout the world. Concrete is primarily composed of aggregate, cement and water. Of which the aggregate is generally composed of coarse gravel or crushed rocks such as limestone, or granite along with fine aggregate such as sand. The presence of aggregate increases the robustness of concrete above that of cement, which otherwise is a brittle material. So, the aggregate especially the coarse aggregate plays an important role for the strength and durability of concrete.

In countries like Bangladesh and parts of India, where natural stone is scarce and hence expensive, crushed burnt clay bricks are extensively used as an economic alternative of coarse aggregate in preparation of concrete. Here, concrete prepared from brick aggregate is commonly used for construction up to six storey buildings, rigid pavements as well as small and medium span bridges and culverts. Fig 1.1 shows a production cycle of brick aggregate from the bricks collected from kiln.

In regions where natural stones are abundant, a survey has shown that about 5 to 10% of bricks manufactured in modern automated factories are rejected due to non-conformity with relevant specifications (Mansur et al., 1996). Utilizing these bricks as coarse aggregate will provide a good use of otherwise waste materials that will also help in alleviating disposal problems. These economic and environmental issues have led to increasing attention and research in properties of brick aggregate and concrete made from it.

Recent successful studies on the use of crushed bricks as aggregate in concrete have been reported from several parts of the world. Akhtruzzaman and Hasnat (1983) carried out some research using well-burnt brick as coarse aggregate in concrete where they found that it is possible to achieve concrete of high strength using crushed brick as the coarse aggregate. Khalaf (2006) determined several physical and mechanical properties of fresh and hardened concrete produced from crushed clay brick aggregate and compared those to concrete produced using granite aggregate. Cachim (2009) found that brick aggregate can be used as partial replacement of natural aggregates in concrete without reduction of concrete properties for 15% replacement and with reductions up to 20% to 30% replacement. Debieb and Kenai (2008) showed that it is possible to manufacture concrete containing crushed bricks (coarse and fine) with characteristics similar to those of natural aggregates concrete provided that the percentage of brick aggregates is limited to 25% and 50% for the coarse and fine aggregate.

Collection of bricks from Kiln

Crushed brick aggregates

Crushing of bricks by brick crusher

Fig 1.1 Production of clay brick aggregates from fresh bricks

Most of the studies mentioned above considered strength, workability and modulus of elasticity as the main parameters for comparison except Debieb and Kenai (2008) who's work include permeability and shrinkage properties of concrete produced from partially replaced brick aggregate.

In a recent paper, Domingo et. al. (2010) studied long term deformation by creep and shrinkage for concrete where natural aggregate is partly substituted by recycled aggregate from waste concrete. Since, creep has important effects on the behavior of concrete structures, as it contributes to the increase in deflection and curvature of beams, cracking, loss of pre-stress in pre-stressing elements and redistribution of stresses in the structures, it is important to know the creep behavior of brick chips made concrete under long term sustained loading.

Nevertheless, very few works has been reported till today that comprehensively deal with creep behavior of concrete produced from newly crushed clay brick as coarse aggregate. There is no extensive data base nor any available model to predict the extent and nature of creep for concrete produced from brick aggregate.

With these as background, present study examines the creep behavior for normal strength concrete produced from brick aggregate. For this, a comprehensive testing program was undertaken at Bangladesh University of Engineering and Technology, Dhaka, Bangladesh where three different normal strength concrete were prepared from both brick and natural stone aggregate. These concrete samples were then tested for creep up to 300 days.

1.2 RESEARCH OBJECTIVES

In the context of discussion in above paragraph, followings are the objectives of this research.

- Evaluation of creep deformation of concrete made of brick aggregate using extensive testing program
- Comparison of the creep response of concrete made of brick chips aggregate to that made of stone chips aggregate
- Examine the effectiveness of widely used creep prediction models to predict creep in brick aggregate concrete and suggest modification factor, if required, so that these models may be used for brick aggregate concrete as well.
- Develop a new, simple, engineering oriented creep prediction model for brick aggregate concrete.

1.3 SCOPE OF RESEARCH

Only normal strength concrete made of both brick and stone aggregate are considered in this study. Creep strain is evaluated as per ASTM C 512-87. Maximum up to 300 days creep strain data are collected. Temperature and humidity is not controlled, rather, room temperature and humidity in the lab surrounding area are measured periodically to be incorporated in the testing results.

1.4 ORGANIZATION OF THE THESIS

The outcomes of the research carried out have been divided into different topics and presented in seven chapters.

In the first chapter, the background of using brick chips as coarse aggregate in concrete is discussed. Furthermore, this chapter points out the emergence and scope of creep testing for brick aggregate concrete.

In chapter 2, an elaborate discussion on creep, its mechanism and the influencing factors are discussed. Moreover, a brief review on the widely used creep prediction models is presented in this chapter.

In the third chapter, an outline of the experimental work is described. Experimentally obtained results for sieve analysis, moisture content, and water absorption are included along with the mix design and compressive strength test results.

In chapter 4, creep test results are presented. Furthermore, a comparison of creep behavior of concrete made from brick and stone chips is analyzed in this chapter.

In the fifth chapter, effectiveness of the widely used creep prediction models is checked against the experimental results. The chapter ends up with proposing the modification factors to the best predicting model to predict creep even better for hot humid climatic conditions.

In chapter 6, a simple and engineering oriented creep prediction model is suggested based on the experimental results, which is related to only two parameters like concrete compressive strength and time.

In the seventh and last chapter, an elaborate conclusion is drawn based on the outcomes of the fourth, fifth and sixth chapters. This chapter also includes possible way forward to explore future research possibilities.

CHAPTER 2

CREEP IN CONCRETE

2.1 GENERAL

Concrete exhibits volumetric changes due to creep which may influence the overall stability of the structure in the long run. This is why, in the design of reinforced concrete or pre-stressed concrete members, long-term deflection may be critical and has to be properly considered. This chapter will provide a clear guideline about creep, its mechanism, factors affecting creep, and widely used prediction models.

2.2 CREEP & RELATED TERMS

Creep is the property of continuing to deform over considerable lengths of time at constant stress or load. According to Vincent, Townsend & Weyers (2004), creep is the time dependent deformation resulting from sustained load whilst accoding to Gambhir (1995), the increase of strain in concrete with time under sustained stress is termed as creep. Creep is considered as a response to a particular type of loading, viz. sustained load, and not a particular kind of inelasticity (Neville, 1970).

Creep may also be viewed from another stand point: if the restraint is such that a stressed concrete specimen is subjected to a constant strain, creep will manifest itself as a progressive decrease in stress with time. This type of relaxation is shown in Fig 2.1. The decrease in stress with time under constant strain is the passive indication of increased strain with the lower stresses than before. The inherent concrete phenomena causing these changes in concrete property may be termed as '*Creep*'.

Creep should be taken as strain in excess of the elastic strain at the time at which creep is being determined. Since modulus of elasticity of concrete increases with age, the elastic deformation gradually decreases and creep is simply taken as an increment in strain above the initial elastic strain. Creep is considered to happen in such a condition that no shrinkage or swelling takes place. If a specimen is drying while under load, it is usually assumed that creep and shrinkage are additive; creep is thus calculated as the difference between the total time-deformation of the loaded specimen and the shrinkage of a similar unloaded specimen stored under the same conditions through the same period. Though shrinkage and creep are not independent phenomena to which the principles of superposition can be applied, and in fact the effect of shrinkage on creep is to increase the magnitude of creep, yet in many actual structures it is noted that creep and shrinkage occur simultaneously and the treatment of the two together is, from practical point of view is inconvenient. This is why, in this research work, creep is considered as a deformation excess of shrinkage. Fig 2.2 illustrates this assumption of research along with the terms and definitions involved.

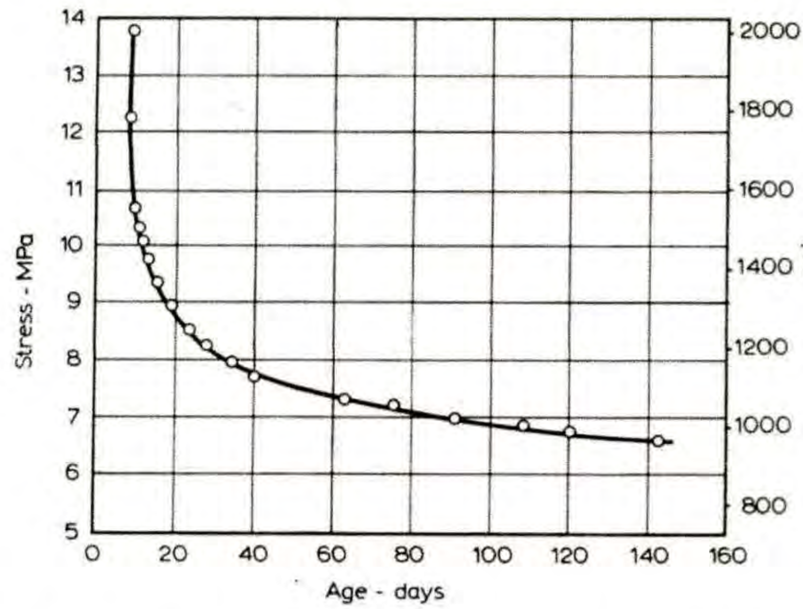

Fig 2.1 Relaxation of stress under a constant strain of 360 x 10^{-6}

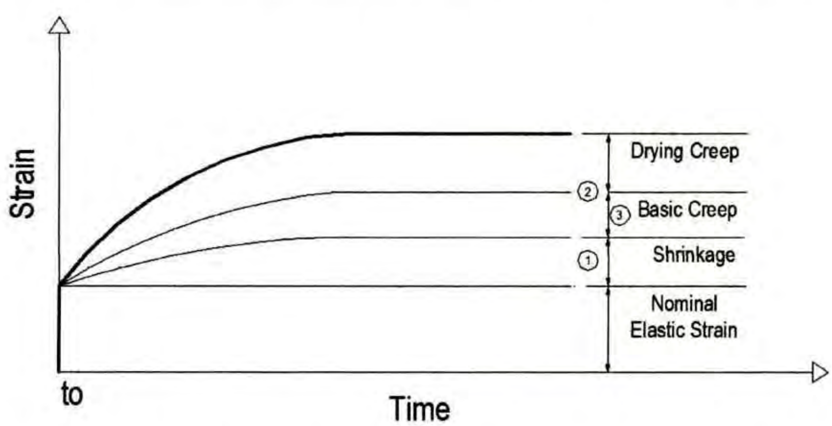

Fig 2.2 Change in strain of a loaded and drying specimen

2.3 CREEP MECHANISM

Creep is a complex phenomenon which is yet to be understood completely. Based on the past experimental findings on creep, it is believed that the origin of creep is in the microstructure of the cement paste binding the aggregate and the sand grains. The basis of this binding agent is the cement gel, which is a very homogeneous material with a colloidal character. It contains chemically bonded water, colloidal water in the gel pores and free water in the capillaries and macro pores. Under the effect of a long-term stress in concrete, the water, which is not bonded chemically, is extruded from the gel micro pores into the capillaries, from which it evaporates. The extrusion of water is determined by the stress of concrete whereas the evaporation depends on the hygrometric conditions of the atmosphere. The time-dependent deformation under sustained load due to loss of water is termed as drying creep. Hence, the magnitude of creep depends on the stress in concrete, concrete mix properties and degree of hydration of concrete. It is also affected by the ambient conditions and temperature.

Under compressive stress, the capillaries structure of cement paste are deformed and the water meniscus displaced outward to a point where the capillary diameter is larger so that the tension under which the capillary water is held decreases. Water will evaporate from the capillaries until the vapor pressure is reduced to the ambient value. The tension in the capillary water rises and the compression in the solid phase increases to maintain equilibrium. The resultant deformation constitutes creep (Neville, 1970).

The seepage theory arises from the observation that hydrated cement paste is a rigid gel, and in such gels generally, load causes an expulsion of the viscous component from the voids in the elastic skeleton, which results a redistribution of stress from the viscous component to the elastic skeleton. Thus creep in concrete is taken to be due to seepage of gel water under pressure (Neville, 1970).

Creep can also result in from the diffusion of micro pore water under stress as shown in Figure 2.3. The thickness of the adsorbed water films that separate C-S-H particles depends on the relative humidity with which the system is in equilibrium. In a saturated paste (100% RH), the equilibrium thickness (te) is about five water molecules thick (about 1.3 nm). If two adjacent C-S-H particles are closer than 2te, the equilibrium films cannot be attained without forcing the particles apart. If the particles are fixed, a disjoining pressure is developed (Mindess et al., 2003).

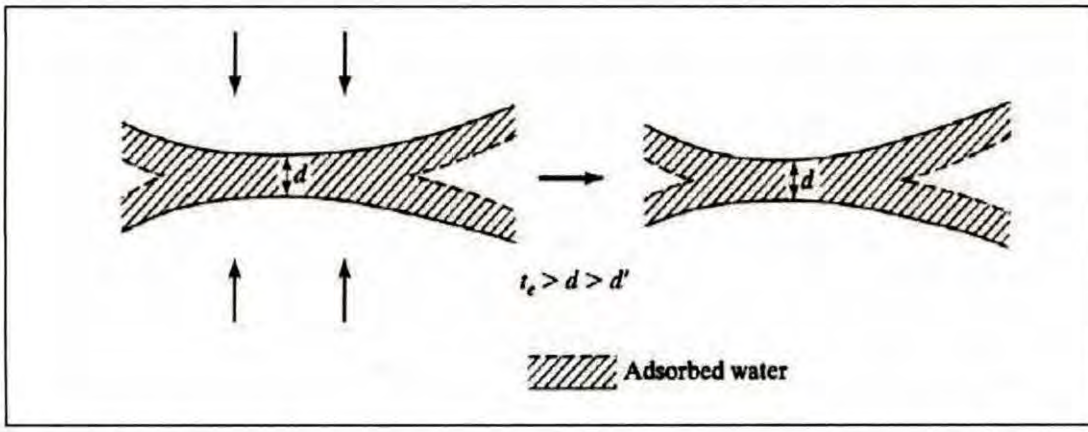

Fig 2.3 Schematic representation of creep due to changes in disjoining pressure

When the external stress is applied, the stress exerted on the water in the micro pores is increased. To maintain equilibrium, the thickness of the absorbed layer must be decreased to compensate for the effective increase in adjoining pressure that has been created. The amount of water redistributed by diffusion is a very small fraction of the total water in the cement paste, so that creep occurs even in saturated specimen without an external loss of water.

The micro cracking is responsible for only a part of the deformation associated with the sustained load. The extent of development of the bond crack due to creep depends on the quantity of bond cracks in existence prior to application of the load. The role of the interface is that of providing a discontinuity when micro cracking takes place. In a pre-cracked concrete, bond cracking does not continue until the sustained load has produced a strain greater than that already experienced (Neville, 1983). Mayers (1967) estimates that micro cracking is responsible for 10 to 25% of the total creep deformation in compression and for creep in tension and creep under cyclic loading the contribution by micro cracking is probably greater. The stress-strength ratio at which micro cracking develops extensively is not constant.

Plastic deformation is the result of slip along the plane of maximum shear in the crystal lattice. Glanville and Thomas (1939) suggested that, creep at low stresses may be viscous and at high stresses in the form of crystalline slip. Against this it may be argued that the creep-time relation for low and high stresses is of the same general form and no fundamental change in behavior is apparent. However, at very high stresses the deformation of concrete resembles somewhat plasticity (Neville et al., 1983).

Viscous flow contributes in some measure to creep of concrete. The basic argument is that hydrated cement paste is a highly viscous liquid whose viscosity increases with time as a result of chemical changes within the structure, possibly crystallization of the particles involved (Neville et al., 1983). Thomas (1937) consider concrete to consist of two parts, cementitious materials and inert aggregates. When the concrete is loaded, the cement flow is resisted by the presence of the aggregate and as a result of this resistance the aggregate become more highly stressed while the stress on the cement paste decrease with time. Since the creep of cement paste is proportional to the applied stress, the rate of creep will be progressively reduced as the load is transferred from the viscous to the inert material.

2.4 FACTORS AFFECTING CREEP

Factors influencing creep include type and the properties of aggregate, water/cement ratio in the concrete mix, curing condition of the specimen, relative humidity of the surrounding environment, stress/strength ratio of concrete, age of concrete at loading and the size of the specimens. These factors are further elaborated in the following.

2.4.1 AGGREGATE

According to Neville (1964), grading, maximum size, and shape of the aggregate have been suggested as factors affecting creep. However, their main influence lies in the effect that they have directly or indirectly on the aggregate content.

Among the certain physical properties of aggregate affecting creep of concrete, the elastic modulus of aggregate has been observed to be the most significant. As the cement paste begins to creep, load is transferred to the aggregate in proportion to the aggregate stiffness. If the aggregate is stiffer, lower stress will be induced to the cement paste, resulting in reduction of paste movement and creep (MacGregor, 1997).

Porosity of concrete has been pointed out to influence the creep of concrete. But this can be interrelated to the elastic modulus of concrete since aggregates with higher porosity generally have a lower modulus of elasticity. On the other hand, it can be visualized that the porosity of aggregate, and even more so its absorption, play a direct role in the transfer of moisture within concrete; this transfer may be associated with creep in that it produces conditions conducive to the development of drying creep. This is the reason why the high initial creep occurs with some lightweight concrete batched in a dry condition.

According to Neville (1983), Troxell was the first to study the effect of aggregate types on creep. Fig 2.4 shows a summary of his results of 20years. It is evident from the curve that the creep of concrete made with sandstone aggregate is 2½ times greater than that of with limestone aggregate. Collins (2002) studied the effect of coarse aggregate size on creep behavior. He found that mixtures with a maximum aggregate size of 1½ inches experienced 15% less creep after 90 days than those with a ¾ inches maximum size.

The aggregate-paste interface strongly affects the aggregate's ability to resist creep. Aggregates with rough surface resist creep much more effectively than those with smooth surfaces. Mokhtarzadeh and French (1990) studied creep of mixture containing five different types of aggregate. It is observed that the mixture containing round river gravel has much higher specific creep values than the other mixtures containing different aggregates.

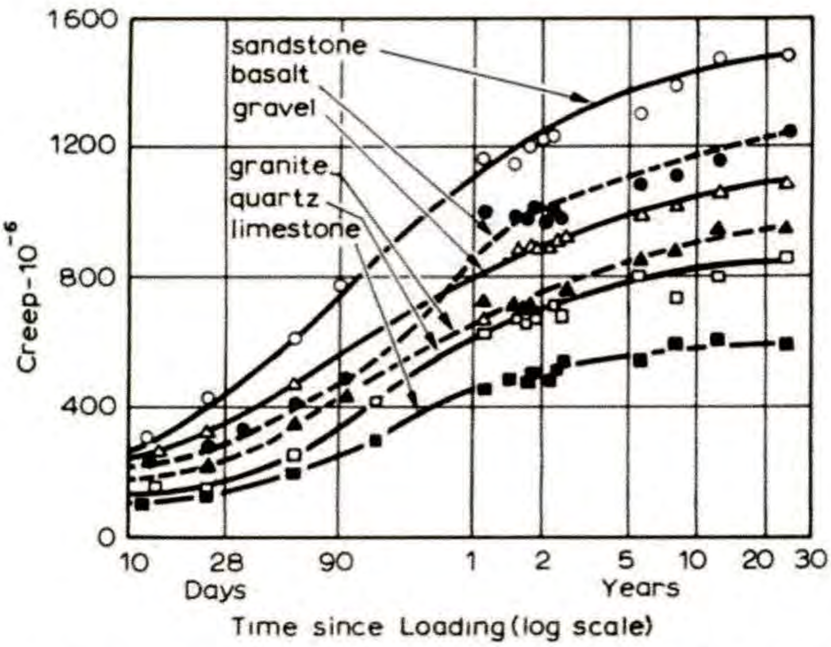

Fig 2.4 Creep of concrete made of different aggregates (Neville, 1983)

2.4.2 WATER CEMENT RATIO

The water/cement ratio has a significant effect on the magnitude of creep. Lower water/cement ratio in the mix leads to higher concrete strength. Thus results in fewer pores in the mature cement, which increases the rigidity of the solid matrix and decrease deformation (Townsend, 2003). The higher the value of water/cement ratio, the greater is the creep.

2.4.3 CURING CONDITION

Curing method can substantially impact the creep behavior of concrete. Steam curing is reported to reduce creep by 30 to 50%. This reduction is due to accelerated hydration of the cement and the moisture loss that occurs when the specimens are transferred to a drier, cooler environment (Huo, Al-Omaishi and Tadros, 2001). Khan, Cook and Mitchell examined the effects of air-dried curing and moist curing on creep of normal, medium and high strength concrete. It is found that higher creep strains occur in the air-dried specimens (Vincent, 2003). Mokhtarzadeh and French (1990) reported that, higher curing temperatures resulted in more creep. They explained this phenomenon as higher temperature increases the porosity and internal cracking of concrete, thereby contribute to creep.

2.4.4 RELATIVE HUMIDITY

The environment surrounding a concrete specimen can greatly affect creep deformations. Orchard (1973) reported that creep is higher at lower relative humidity. Neville (1983) also noted that drying concrete creeps at a higher rate and achieves higher ultimate creep than concrete which remains wet. This is illustrated in Fig 2.5 for specimens cured at a relative humidity of 100% and then loaded and exposed to different humidity. It is found that at relative humidity of 50%, creep is two or three times greater than concrete at relative humidity of 100%.

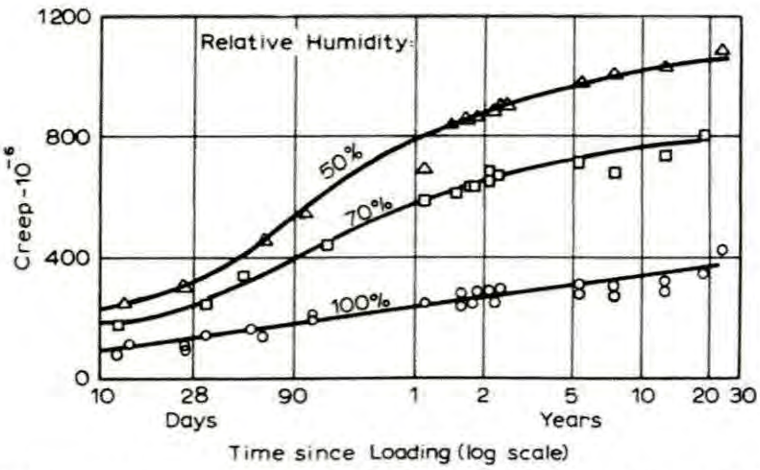

Fig 2.5 Creep of concrete at different relative humidity (Neville, 1983)

2.4.5 STRESS/STRENGTH RATIO

Creep of concrete is highly sensitive to the magnitude of sustained stress applied (Tadros et al, 2002). For instance, a specimen loaded to 80% of its ultimate strength experiences creep about three times greater than similar specimen loaded to 40%. Micro cracking at the aggregate-paste interface becomes more significant at higher stresses. Delayed failure may occur at sustained stresses above 75% of the compressive strength (Bazant and Baweja, 1995).

Smadi, Slate and Nilson performed creep tests on high, medium and low strength concrete and investigated the response to sustained stress levels between 40 and 80%. They found that the creep strain is proportional to the stress level, up to a certain proportional limit. The limit is about 65% of ultimate for high strength concrete and 45% of ultimate for normal strength concrete and low strength concrete. These results imply that high strength concrete can be safely loaded to a higher fraction of its ultimate strength and without experiencing excessive time-dependent deformations (Townsend, 2003).

Above the limit of proportionality, creep increases with the increase in stress at an increasing rate and there exists a stress/strength ratio above which creep produces failure. This stress/strength ratio is in the region of 0.8 to 0.9 of the short-term static strength. Creep increase the total strain until this reaches a limiting value corresponding to the ultimate strain of the given concrete.

Within a wide range creep is inversely proportional to the strength of concrete at the time of application of load. It is thus possible to express creep as a linear function of the stress/strain ratio (Fig 2.6).

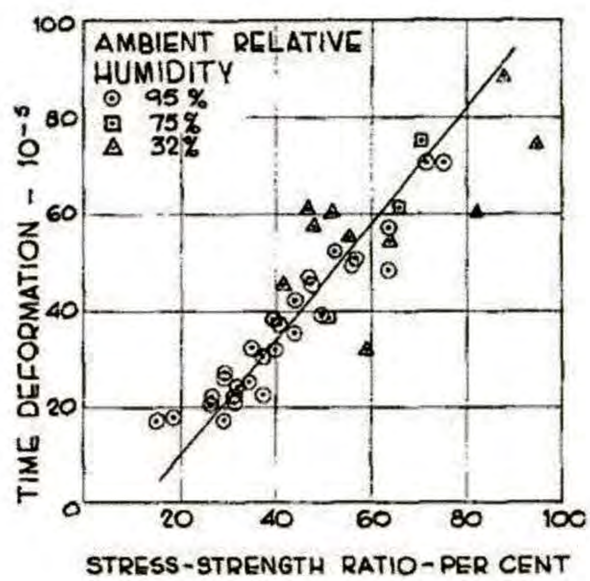

Fig 2.6 Variation of creep with stress/strength ratio (Neville, 1959)

2.4.6 AGE OF LOADING

Another factor affecting creep is the concrete age when a sustained load is applied. Specimens loaded after one day of curing typically have twice the specific creep of specimens loaded after 28 days. It is due to the fact that if the concrete has not been given adequate time to cure, it will not have the stiffness needed to resist creep (Bazant and Baweja, 1995). In particular, Khan, Cook and Mitchell observed that high strength concrete is much more sensitive to early-age loading than normal strength concrete (Townsend, 2003).

2.4.7 SIZE OF SPECIMEN

Tests had been done by Weil to investigate the influence of the size of the specimen on creep. It is found that creep decreases with an increase in the size of the specimen. This is due to the fact that, the drying process in a larger specimen is slower, thus reducing creep. However, the size effect becomes negligible when the specimen thickness exceeds about 0.9m (Neville, 1983). The size effect can best be expressed in terms of the volume/surface ratio of the concrete member as shown in Fig 2.7. It can be observed that at a particular time the higher the volume/surface ratio the lesser the creep of concrete.

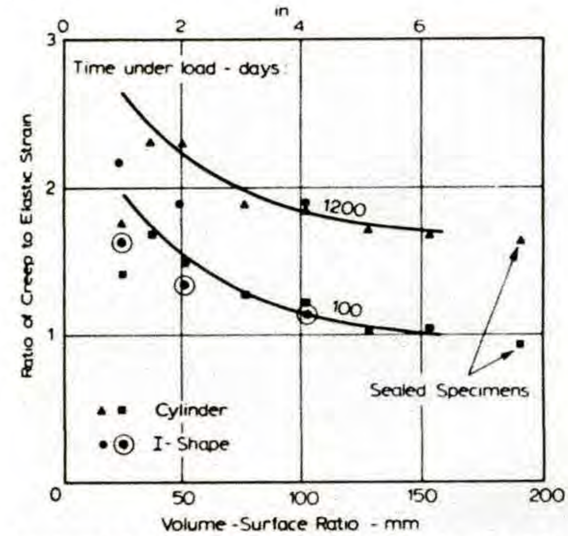

Fig 2.7 Creep ratio and volume/surface ratio relationship (Neville, 1963)

2.4.8 PROPERTIES OF CEMENT

The type of cement affects creep in so far as it influences the strength of the concrete at the time of application of the load. This is why any comparison of creep of concrete made with different cements should take into account the influence of the type of cement on the strength of concrete at the time of application of the load.

Fineness of cement affects the strength development at early ages and thus influences creep. Extremely fine cements, with a specific surface up to 740 kg/m^2, lead to a higher early creep but to lower creep after one or two years under load (Bennett,1970). For a constant applied stress at a fixed age, creep increases in order for: rapid-hardening, ordinary, and low heat cements (Neville, 1963).

2.4.9 TEMPERATURE

The influence of temperature on creep is significantly important in pre-stressed concrete nuclear pressure vessels as well as in other types of structures like bridges. The rate of creep increases with temperature up to about 70°C when, for a 1:7 mix with a water/cement ratio of 0.6, it is approximately 3.5 times higher than at 21°C. The rate drops off to 1.7 times the rate at 21°C in between 70°C and 96°C (K. W. Nasser, 1965). These differences in rate persist at least for 15 months under load. This behavior may be due to desorption of water from the surface of the gel. It is also possible that a part of the increase in the creep of concrete loaded at elevated temperatures may be due to the lower strength of concrete at high temperatures. (Dias, 1990)

2.5 ENGINEERING PROPERTIES OF CONCRETE

Engineering properties of concrete reviewed in this section are compressive strength and modulus of elasticity. These engineering properties are important and useful for the prediction of creep of concrete.

2.5.1 COMPRESSIVE STRENGTH

Most concrete structures are designed under an assumption that the concrete resist compressive stresses but not tensile stresses, hence for purposes of structural design the compressive strength is the criterion of quality (Troxell et al., 1968). This is because compressive strength for concrete is so much greater than tensile strength. Compressive strength is the maximum load per unit area sustained by a concrete specimen before failure in compression (Akroyd, 1962).

The compression test is relatively easy to do. Cubes, cylinders and prisms are the three types of compression test specimens used to determine the compressive strength. Increment of time and temperature increases the compressive strength of concrete. The direct relationship of strength to maturity varies with the composition of the concrete and the type and quality of the cement used (Akroyd, 1962).

2.5.2 MODULUS OF ELASTICITY

Concrete is the material which distorts under the influence of applied forces. Concrete is partially elastic since it suffers from creep during loading. Elasticity is measured by modulus of elasticity which is a measure of resistance to deformation (Akroyd, 1962). The modulus of elasticity is defined as the change of stress with respect to elastic strain (deformation) and may be computed from the Equation (2.1) (Troxell, 1968).

Modulus of elasticity = (unit stress / unit strain)............................. (2.1)

However, there are numerous empirical equations which can be used to compute the elastic modulus of concrete. One of them is $E_c = 57000\sqrt{f'_c}$, which is one of the popular equations directly related to the compressive strength of concrete.

2.6 WIDELY USED CREEP PREDICTION MODELS

Four of the prediction models for creep are described in this section. The ACI 209 model is recommended by the American Concrete Institute. The CEB-FIP Model Code 90 is used in Europe. Other models include the B3, which was developed by Bazant, and GL model, which was developed by Gardner. The models look at free shrinkage, creep strain, and elastic deformation. The creep strain is the combination of the basic and drying creep. The elastic deformation is the instantaneous recoverable deformation of a concrete specimen during the loading process. The various creep models relate the creep strain to the loading conditions by using creep coefficient, specific creep or creep compliance. The creep coefficient is the ratio of creep strain at given time to the initial elastic strain. Specific creep is the creep strain per unit stress. The creep compliance is the ratio of creep strain plus elastic strain per unit stress. All these models are provided in Appendix A.

2.6.1 ACI 209R-92 MODEL

The ACI 209 model was developed by the American Concrete Institute and is used in the AASHTO LRFD method. The ACI 209 Model was created from data that included normal weight, and lightweight concrete. It also incorporates Type I (Normal Portland Cement), and Type III cement (High early strength cement). It is found that there is no significant difference between different weight concretes for creep and shrinkage. The code notes that more consistent results are found by using the creep coefficient or the ratio of creep strain to initial strain. This is due to the initial stiffness of the concrete being accounted for. The code allows for the following variation to the standard conditions: concrete composition, age at loading, ambient relative humidity, size factor, and ambient temperature. The concrete composition correction factors apply to slump, fine aggregate percentage, cement content, and air content. Either the average thickness method or the volume to surface ratio method can adjust the size factor. The volume to surface area ratio is used since it is more applicable to pre-stressed concrete beams.

2.6.2 CEB-FIP 90 MODEL

The CEB-FIP Model Code 90 is the European design code recommended by the Euro-International Concrete Committee and International Federation for Pre-stressing. This model is preceded by the CEB-FIP 1970 model and the CEB-FIP 1978 model. The CEB-FIP 1970 model is a model that adjusted for mix properties and environmental conditions with multiplication factors from graphs. The CEB-FIP 1978 model is a summation model that has correction factors that needed to be summed from graphs. The CEB-FIP 90 is a prediction model, which is designed to predict the mean time dependent deformation for normal weight, plane structural concrete. It only takes into account parameters that are generally known to the designer in the design stage. The CEB model has a coefficient of variation of 20.4% and 32.9% for creep compliance and shrinkage respectively. The following parameters are required to predict the creep coefficient: mean or design strength of the concrete, member dimensions, mean relative humidity of the ambient atmosphere, age at loading, and duration of loading. In addition to these parameters, the cement type is needed to predict shrinkage strain.

2.6.3 B3 MODEL

The B3 model is the creation of Z. P. Bazant and S. Baweja. Earlier versions of the model are the BP model in 1978 and the BP-KX model in 1991. The BP-KX has an expanded and a short form. The expanded form is for structures highly sensitive to creep and shrinkage. The short form predicts creep compliance in a design code method. The B3 model is designed to meet the requirements of the RILEM TC 107 for a simpler model. The B3 model can be applied to concretes outside the limitations if the parameters are calibrated with tests.

2.6.4 GL2000 MODEL

N. J. Gardner and M. J. Lockman developed the GL2000 Model as a design office procedure to predict creep and shrinkage. Gardner and J. W. Zhao's GZ Model from 1993 preceded this product model. The predicted values can be improved by measuring the compressive strength and modulus of elasticity. This model uses the modulus of elasticity and compressive strength measurements to adjust for aggregate stiffness. Aggregate stiffness is a factor in elastic deformation, creep, and shrinkage. The GL2000 model uses the experimental modulus to have a compressive strength back calculated from it. This value is averaged with the compressive strength and an adjusted modulus is calculated. The creep coefficient prediction uses the time at loading, time at the beginning of shrinkage, volume to surface area ratio, and the ambient relative humidity. The model has a factor, Φ (tc), to adjust for moisture loss before loading. If the time of loading is equal to the time at the beginning of shrinkage, then Φ(tc) equals one. The specific creep is found by dividing the creep coefficient by the adjusted modulus of elasticity. The instantaneous elastic strain can be found by dividing the applied load by the modulus of elasticity at the time of loading. Shrinkage strain is predicted with correction factors for the effect of cement type on shrinkage, the effect of time on shrinkage using the volume to surface ratio, and humidity. The ultimate shrinkage strain is a function of the mean 28-day compressive strength.

CHAPTER 3

CREEP PREDICTION: RESEARCH METHODOLOGY

3.1 GENERAL

The basic intent of this chapter is to design an outline for the research work which includes a series of testing like sieve analysis, absorption capacity of aggregate, field moisture content of aggregate, crushing strength of bricks etc. followed by compressive strength test and creep test of concrete specimen. All these tests are performed in the concrete laboratory of BUET, in accordance with the standard testing procedure of ASTM.

3.2 CREEP TEST METHODOLOGY OF CONCRETE MADE OF BRICK CHIPS

As discussed in chapter 1, concrete made of brick chips is most commonly used in the construction work of Bangladesh. Generally, bricks are gathered from kilns in Bangladesh. Though machine made bricks are not that uncommon now a days. These brick kilns are of various qualities. They produce wide variety of bricks. In order to get the representative result, bricks from three different kilns were collected to perform the test.

Some general tests of bricks like water absorption test, moisture content test, crushing strength of bricks were performed in the laboratory. Tests of aggregates (both fine & coarse) like sieve analysis, moisture content were also performed to get the fineness modulus (F.M) & water absorption of the aggregate.

Based on the test results, a mix design was established to get the required strength of concrete, which were counterchecked by the compressive strength test after 7 & 28 days as per ASTM C39-86.

Finally, the creep test was performed as per ASTM C512-87 in the laboratory condition. Fig 3.1 shows the flow diagram of the research methodology relating the creep testing of concrete made of brick chips while Fig 3.2 shows the flow diagram for the creep testing of concrete made of stone chips.

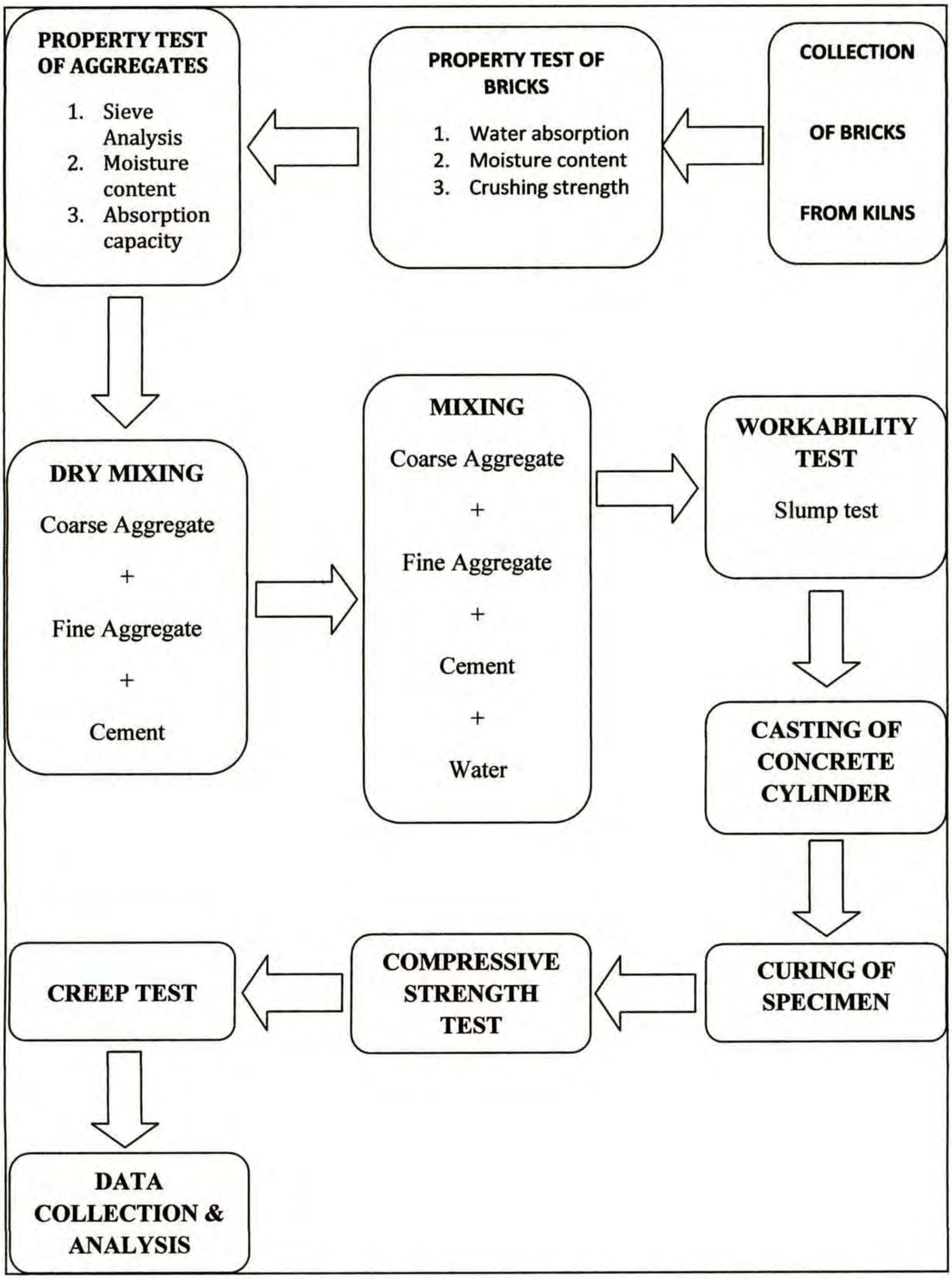

Fig 3.1 Flow diagram of creep test methodology of concrete made of brick chips

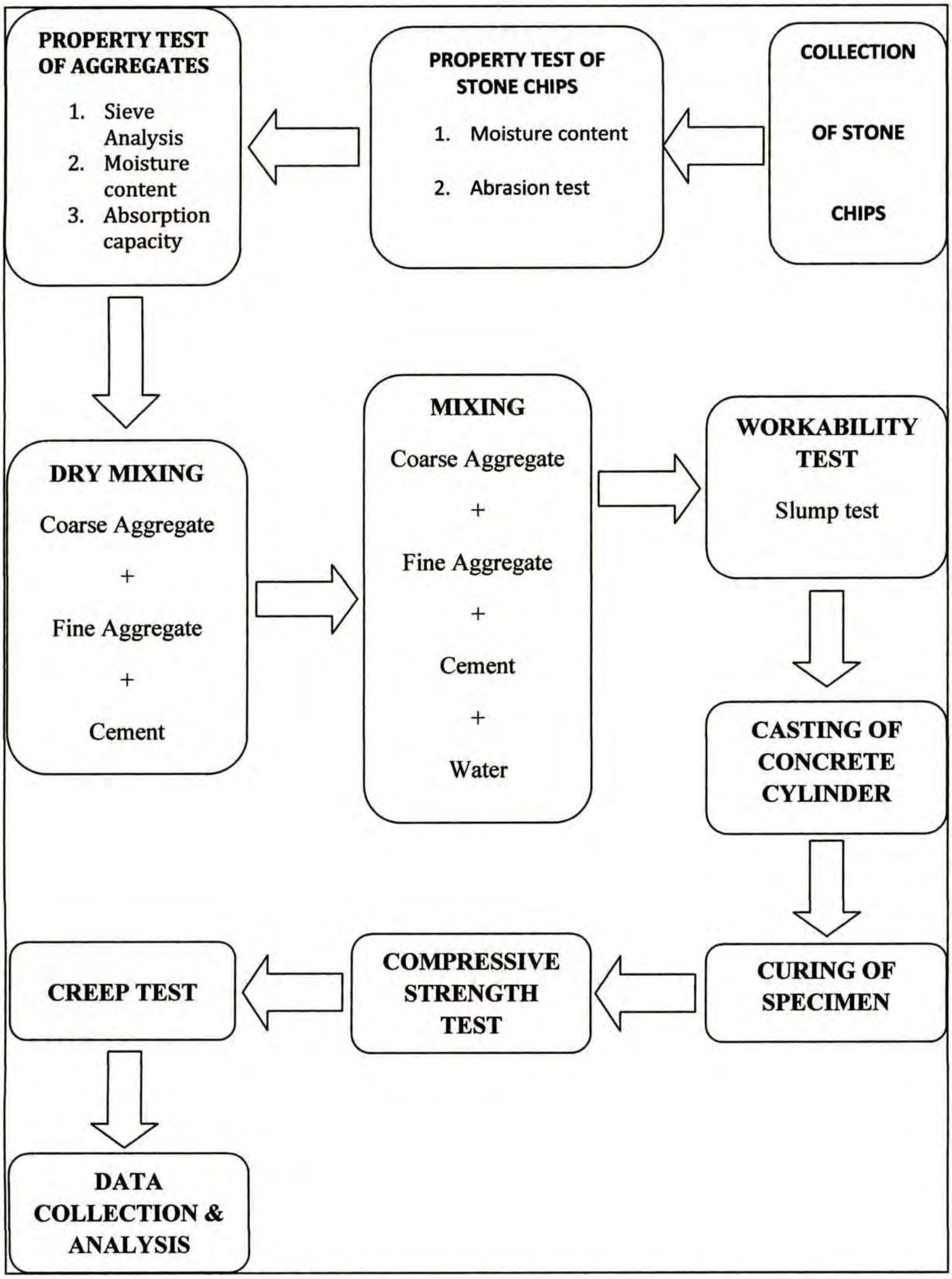

Fig 3.2 Flow diagram of creep test methodology of concrete made of stone chips

3.3 TESTING MATERIALS & TESTING SPECIFICATIONS

3.3.1 CEMENT

Ordinary Portland cement (Type 1) having 28 days compressive strength of 46 MPa (ASTM 1994) was used for preparation of all concrete samples. By using one type of cement the effect of varying the types of coarse aggregate in concrete can be investigated.

3.3.2 FINE AGGREGATE

Best quality coarse sand (brown in color) locally known as 'Sylhet sand' was used as the fine aggregate. A single type of natural coarse sand was used throughout the experimental work so as to keep the fine aggregate parameter constant. The sieve analysis was carried out in accordance with ASTM C136 (ASTM 2006). The sieve analysis result showed that the used sand was well graded having fineness modulus (F.M) in the range of 2.6 to 2.8 and fitted within the limits set out in ASTM C33 (ASTM 2003).

3.3.3 COARSE AGGREGATE

Clay Bricks

Bangladesh standard BDS 208:2002 (BSTI 2007) classify bricks into three categories depending on its use. Of these three, type 'S' is normally used for aggregate production and the same has been employed in this work. Before the new bricks were crushed down into coarse aggregate, their compressive strength was measured as per ASTM C67-03a (ASTM 2009) and was found to be 31.9 MPa which is above 27.5 MPa, the limit set in BDS 208-2002 (BSTI 2007) for Type 'S' bricks.

Clay brick and stone aggregate

In order to get the superior quality brick chips, best 'picked jhama' bricks were collected from three different kilns having frog marks 'NBM', 'EBS' and 'MEB' respectively. After necessary property testing like moisture content, water absorption, crushing strength test, these bricks were crushed into ¾ inch maximum sizes and were used as coarse aggregates. Brick aggregate was produced by breaking down whole new bricks on a solid concrete surface using hammer. Natural crushed sandstone boulders were used as stone aggregate. For comparison purpose, bricks and stone boulders were crushed in a way that they possess similar gradation and approximately same fineness modulus (FM) to negate the effect of size and shape on creep behavior of concrete. Additionally, it was also ensured that grading limits set out in ASTM C33 (ASTM 2003) is strictly maintained. Size distribution and gradation of both type of aggregate achieved from these concepts are shown in Fig 3.3 from which, FM of stone and brick aggregate were found to be 8.3 and 7.9 respectively. For comparative creep testing, stone chips having ¾ inch maximum sizes were used.

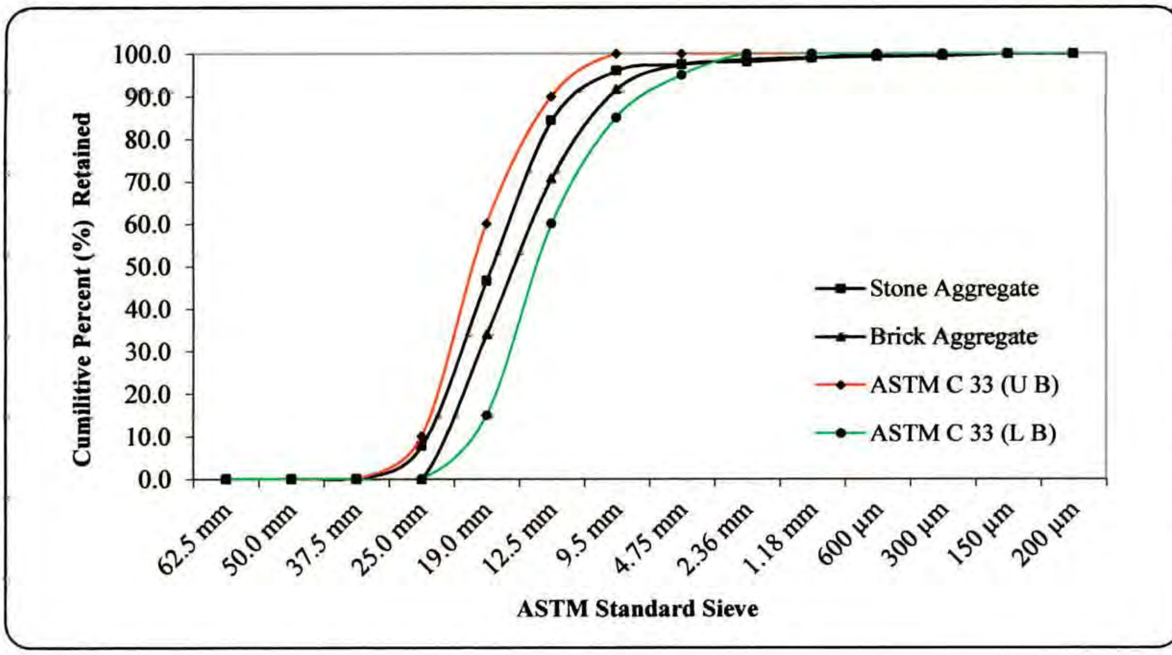

Fig 3.3 Gradation of Natural Stone and Brick Aggregate

3.3.4 SIEVE ANALYSIS

The sieve analysis consists of shaking the aggregate (both coarse & fine) through a stack of wire screens with opening of known sizes as per ASTM C136. For a single sieve analysis 5kg of coarse aggregate requires. A horizontal motion and rotation for 10 minutes differentiate the materials in different sieve. The weights of the materials retained in different sieve were taken and thus the gradation of the material was found with the help of the gradation curve. Fig 3.3 shows the result of the sieve analysis for natural stone and brick aggregate.

3.3.5 ABSORPTION TEST

In order to perform this test, each brick from each category were taken and were divided into two parts. Half of each brick were kept in a jar full of water for 24 hours. The rest half were kept in oven to make it oven dry. The difference in weight in percentage gave the water absorption capacity of each specimen. This test method conforms to ASTM C127.

$$water\ absorption\ (\%) = \frac{[wt.of\ saturated\ sample - wt.of\ oven\ dry\ sample]\ x\ 100\%}{wt.of\ oven\ dry\ sample} \quad .... (3.1)$$

The average water absorption capacity of the bricks used for the coarse aggregate was found as 17.2%.

3.3.6 MOISTURE CONTENT TEST

The difference in weight between the sample at field condition and the sample at oven dry condition indicates the moisture content of that particular sample. The computed average field moisture content was 13.2%.

3.3.7 WATER

Water is a key ingredient in the concrete production. As per ACI manual for construction, the property of water that will be used in the concrete work should be potable, free from oil and other organic impurities. In this particular research work, ordinary tap water was used as mixing water throughout the mixing procedure which possesses all the requirements described in ACI manual for construction.

3.3.8 MIX DESIGN

The procedure for design of concrete mixes with normal aggregate was used to design mixes using crushed brick aggregate. In this work, mix design ratios for both stone and brick aggregate with target strength of 17.2 to 27.5 MPa were evaluated from ACI method (ACI 2002). Design ratios were evaluated by keeping a constant volume for both stone and brick aggregate so that the variation in creep behavior of concrete due to parameters other than the properties of coarse aggregates remains minimal. Mix ratios thus evaluated are converted to equivalent weight and are shown in Table 3.1.

Table 3.1 Concrete Mix Design (weight basis)

		Weight (kg)				
	Target strength (MPa)	w/c	OPC	Coarse aggr.	Fine aggr.	Water
Brick aggr.	17.2	0.55	26.4	87.1	67.2	14.6
	24.0	0.42	30.0	87.1	62.9	12.7
	27.5	0.37	34.3	87.1	59.5	12.7
Stone aggr.	17.2	0.58	22.8	81.3	68.4	13.2
	24.0	0.40	30.0	81.3	64.9	12.0
	27.5	0.38	34.3	81.3	60.5	12.5

(Quantity for single batch: 12 cylinders per batch)

Table 3.2 shows strength test results on concrete samples prepared using mix ratios of Table 3.1. From these results, it may be seen that except one instance (30.2 MPa in case of 27.5) the achieved strength is fairly closer and lies within 5% of the target strength. Therefore, it may be stated that the applied mix ratios were appropriate and justified. Results in Table 3.2 also indicate that strength rather than types of aggregate used is the main determining factor for modulus of elasticity of concrete. This is in accordance with findings of other researchers e.g. Cachim (2009).

3.3.9 CONCRETE MIXING

Before mixing the concrete, cement was kept dry and placed in a moisture-proof container to prevent the initiation of hydration and difficulties in handling. Fine and coarse aggregate was maintained in a saturated surface-dry condition 24 hours prior to use. All the concrete materials were stored at room temperature in the range of 20° to 30°C in accordance with ASTM C 192-90a (1990).

It is important to have proper mixing to ensure all surfaces of the aggregate particles were coated with cement paste and the ingredients were blended into a uniform mass. In this study, the drum type mixer was used. The workability tests adopted in this investigation was slump test for the concrete. The slump test was carried out in accordance to ASTM C143-90a (1990).

3.3.10 CURING OF SPECIMEN

Concrete must be properly cured to develop its optimum properties. To prevent evaporation of water from the un-hydrated concrete, the specimens were immediately covered with wet gunny sack after molding. The specimens were removed from the molds after 24 ± 8 hours (ASTM C192, 1990), moist cured at 23° ±1.7°C until the age of 7 days in accordance with ASTM C 512-87.
After the completion of moist curing, the specimens were loaded for compressive strength test leading creep test and stored at the control room until completion of the test.

3.3.11 COMPRESSIVE STRENGTH TEST

Cylinder specimens having 150mm diameter and 300mm height were prepared for compressive strength test. The specimens prepared were the same as specimens prepared for creep test and were tested at the age of 7 and 28 days. The compressive strength test was performed in accordance with ASTM C 39 (1993).

The specimens were tested in a compression machine as shown in Fig 3.4 in the concrete laboratory of BUET with a loading rate of 3.0 kN/sec. The load was applied continuously until the specimen fails and the maximum load carried out by the specimen during the test was recorded. Table 3.2 shows the obtained result of compressive strength test.

Fig 3.4 Compressive Strength Testing Machine

Table 3.2 Concrete Compressive Strength Test Result

	Target strength (MPa)	compressive strength (MPa)		Modulus of Elasticity (GPa)
		7 days	28 days	28 days
Brick aggr.	17.2	12.4	17.8	21.0
	24.0	17.6	25.1	25.0
	27.5	19.4	27.7	26.0
Stone aggr.	17.2	12.3	17.7	21.0
	24.0	17.7	25.2	27.0
	27.5	21.2	30.2	29.0

3.4 CREEP TEST

3.4.1 PREPARATION OF SPECIMEN

Vertically casted cylindrical specimens having size of 150mm x 300mm were prepared in accordance with the provisions of ASTM C 512 (1987) for creep testing. For each compressive strength category, two cylinders were used for creep testing. One of them was loaded in the test rig and the other was kept unloaded in the controlled environment. Fig 3.6 shows typical creep testing specimen.

While casting, the concrete were placed in two approximately equal layers and each layer was compacted 25 times uniformly over the cross section of the mold. After consolidation, the top surfaces were finished by fitting the ends with Perspex plates normal to the axis of the cylinder to get the flat surfaces. Then the specimens were covered with wet gunnysack to protect water from evaporation and then the curing process was maintained as mentioned in Section 3.3.10.

For creep testing, a strain meter was used to measure the deformation of the concrete cylinder as shown in Fig 3.5. Before testing, two strain measurement points (studs) were glued at 200 mm distant apart on two opposite side of each concrete specimen as shown in Fig 3.6.

Fig 3.5 Strain Meter

Fig 3.6 Gauge Stud and Typical Creep Testing Specimen

3.4.2 CREEP TESTING APPARATUS

According to ASTM C 512-87 (1987), the loading frame used for creep testing must be capable of applying and maintaining the required load on the specimens. The loading frame consists of header plates bearing on the end of the loaded specimens, a load-maintaining element either spring or a hydraulic capsule or ram, threaded rod to take the reaction of the loaded system.

In this study, the creep test was carried out using the creep test rig. Coil spring loading system was selected as the loading frame. The coil spring was installed between lower base plate and upper base plate. The sustained stress was applied by tightening the four tie rods and a load cell was permanently installed in the frame when the load was applied. The creep test rig was able to hold three concrete specimens in series. Fig 3.7 & 3.8 show the arrangement of specimens for creep testing along with loading cell.

Fig 3.7 Loading Frame with Samples for Creep Testing

Fig 3.8 Load Cell for Creep Testing

3.4.3 CREEP TESTING PROCEDURE

Creep test was carried out at the concrete age of 7 & 28 days. Before loading the creep specimens, the compressive strength of the specimen was determined in accordance with standard test method of ASTM C 39 (1993). The average ultimate compressive strength of three specimens was used to determine a stress which was being applied to specimens for creep test. The manual loading system for creep test was subjected to a load equivalent to a stress of 35% of average ultimate compressive strength as stress-strength ratio.

The specimens were placed in the loading frame as shown in Fig 3.8. The center point of each plate was determined and the specimens were placed with caution to avoid eccentricity. After loading, both control and loaded concrete cylinders were kept under room temperature of 28±4° C. Relative humidity at the place of testing frame was also recorded for the entire loading period and its distribution is shown in Fig. 3.9.

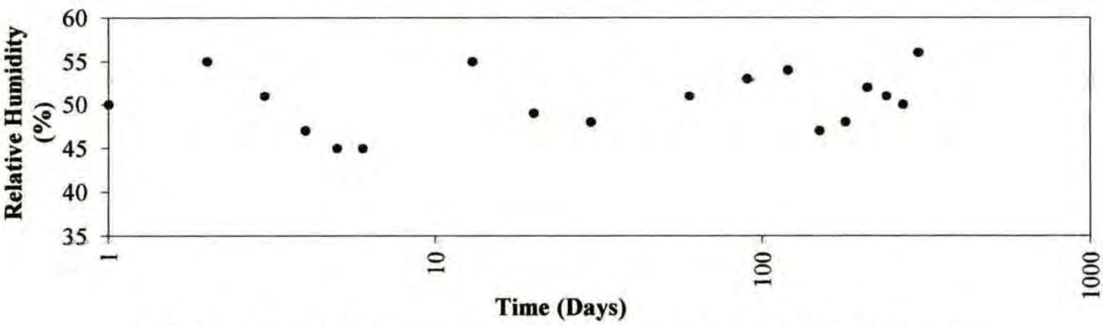

Fig 3.9 Relative humidity in and around the creep testing machine

The actual load applied was monitored using a load cell. The load was measured every time before each strain reading was taken to ensure the correct value of loading was applied. The strain reading was taken immediately before and after loading, two to six hours later, and then daily for 1 week, weekly until the end of one month and monthly until the end of the testing. The strain values of loaded specimen as well as that of control specimens were measured using 200mm strain gauge. Strain in the control specimen is, in effect, due to shrinkage, temperature and other secondary causes except creep. The magnitude of deformation was obtained when the strain of the control specimens and elastic deformation is subtracted from the total deformation of loaded specimen. Then the creep strain was obtained by multiplying the above reading with a calibration factor of 0.002 mm.

3.4.4 CREEP CALCULATION

(a) TOTAL CREEP

The total creep strain is obtained by subtracting the instantaneous elastic strain and strain in control specimen from the total strain as given in the following equation.

$$C\,(t1,\,to) = [\varepsilon t\,(t1) - \varepsilon ie\,(to)\text{-stain in control specimen}]^{*}\,M \quad \text{........................... (3.2)}$$

Where,
C (t1, to) = total creep at time t1 due to a stress applied at to
εt (t1) = total deformation at t1
εie (to) = instantaneous elastic strain at time to
M = coefficient of strain meter

(b) CREEP COEFFICIENT

Once, the creep value obtained from above equation, the creep coefficient is obtained as a ratio of creep to the instantaneous elastic strain at any age.

$$\Phi\,(t1,\,to) = C\,(t1,\,to)\,/\,\varepsilon ie\,(to) \text{.......................... (3.3)}$$

Where,
Φ (t1, to) = creep coefficient at t1 due to a stress applied at time, to
C (t1, to) = total creep at time t1 due to a stress applied at time, to
εie (to) = instantaneous elastic strain at time, to

However, a more explicit expression of creep coefficient is represented in equation 5.1 where creep coefficient is directly related to creep strain, applied stresses and modulus of elasticity.

CHAPTER 4

CREEP COMPARISON OF CONCRETE MADE OF BRICK AND STONE CHIPS

4.1 GENERAL

Due to the scarcity of stones, crushed clay brick, i.e. brick chips are extensively used as coarse aggregate in preparation of concrete as an economic alternative. Properties of brick chips as aggregate vary appreciably from stone chips or shingles in the context of strength, toughness and other related index. Since coarse aggregate occupy a large share of concrete volume, therefore, it is presumable that the creep property of concrete made of brick chips will differ from that made of stone chips as coarse aggregate. However, very few works has been done till today to examine the effects of incorporating brick chips as coarse aggregate on the creep behavior of concrete.

The intent of this chapter is to examine the differences in creep behavior for normal strength concrete produced from both brick chips and stone chips as coarse aggregate in Bangladeshi environment. Based on the data obtained from the experimental works carried out at Bangladesh University of Engineering & Technology, Dhaka for concrete having characteristic compressive strength of 17.2 N/mm^2 to 27.5 N/mm^2, a comparative study is conducted to examine the differences in creep behavior for concrete made from two different types of coarse aggregates i.e. brick and stone chips.

4.2 EXPERIMENTAL OUTCOMES

At the end of the comprehensive testing program outlined in chapter 3, the following results are obtained in response to the comparison of creep of brick and stone aggregate concrete. Fig. 4.1 to 4.6 shows creep strain for both brick and stone aggregate concrete of three different strength and loaded at 7th and 28th day after casting.

From these graphs, it is apparent that creep strain-time relations have similar pattern for both type of concrete. There is an initial steep slope of strain increase after which, rate of increase remains approximately constant over the 300 day time period. Nevertheless, in brick aggregate concrete, creep strain is always higher than that of stone aggregate concrete of same strength. The reason behind this might be the higher water demand of brick chips than the stone chips which eventually get released when the specimen is subjected to a sustained load.

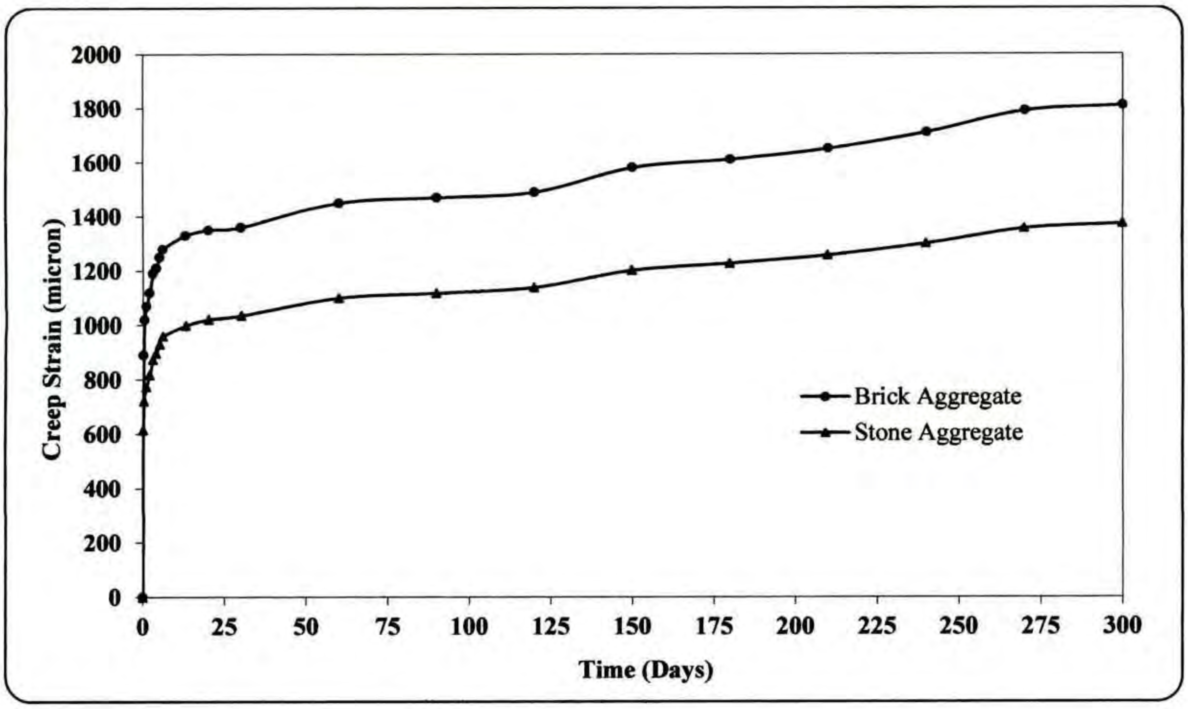

Fig 4.1 Comparison of creep strain for 17.2 MPa concrete loaded at 7th day

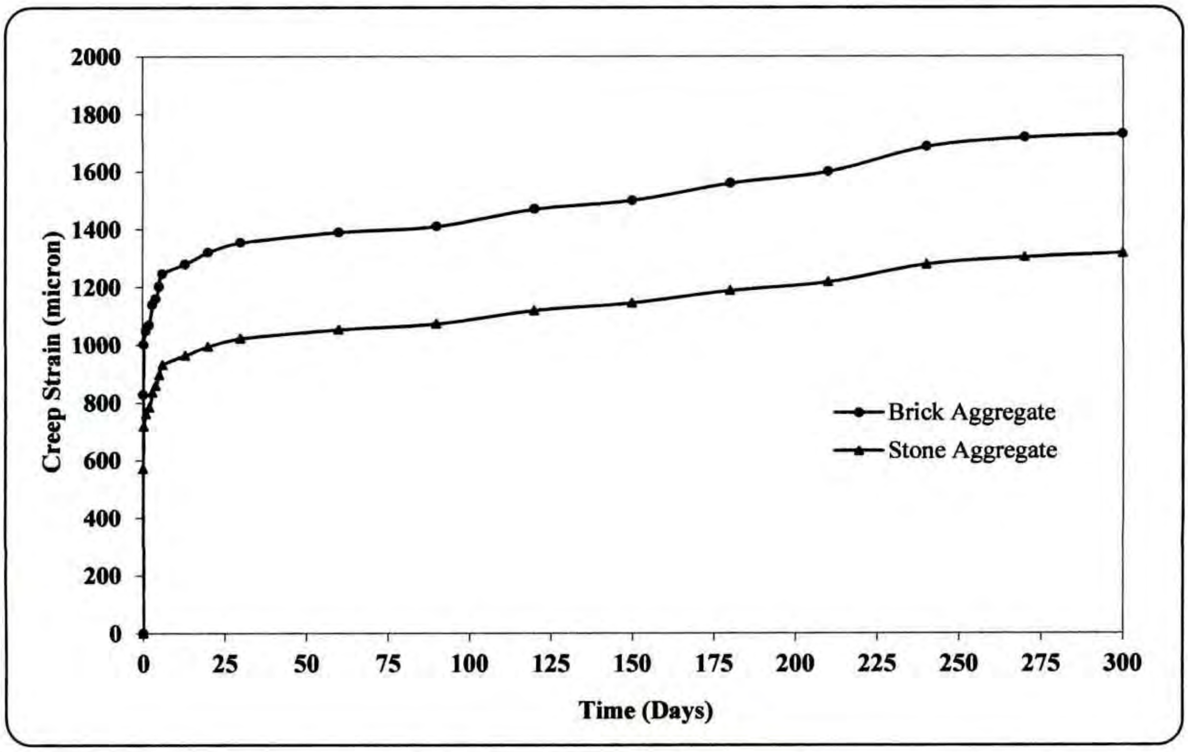

Fig 4.2 Comparison of creep strain for 24.0 MPa concrete loaded at 7th day

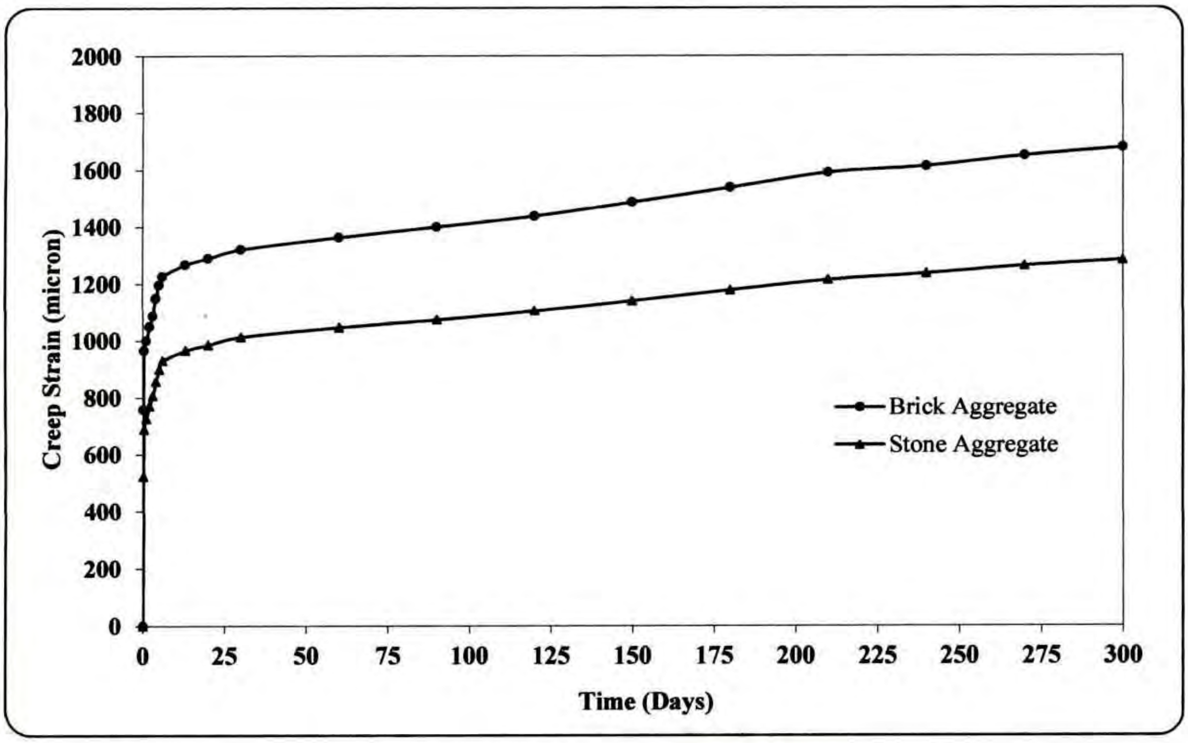

Fig 4.3 Comparison of creep strain for 27.5 MPa concrete loaded at 7th day

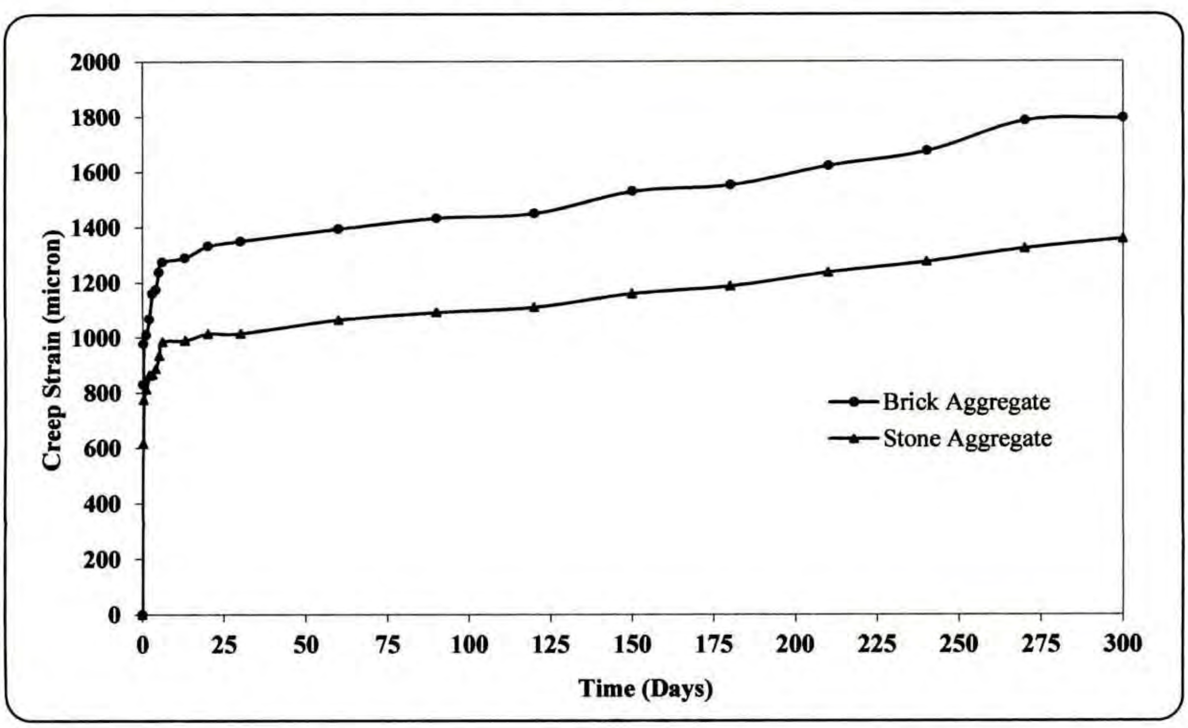

Fig 4.4 Comparison of creep strain for 17.2 MPa concrete loaded at 28th day

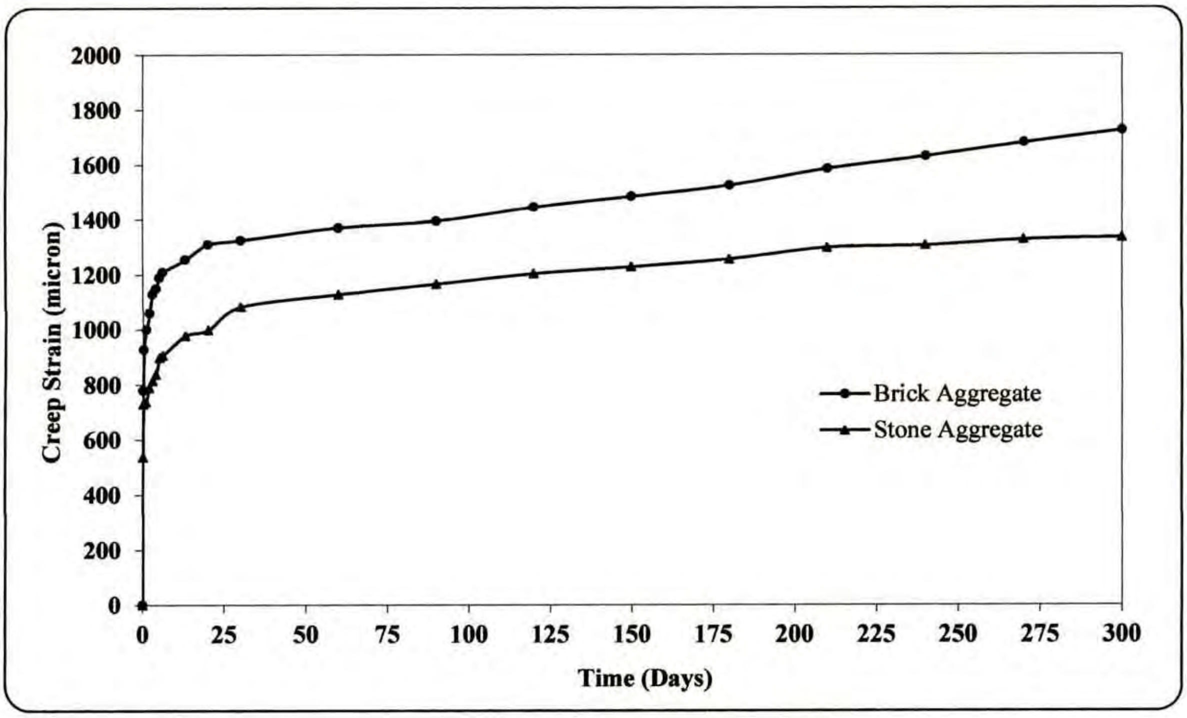

Fig 4.5 Comparison of creep strain for 24.0 MPa concrete loaded at 28th day

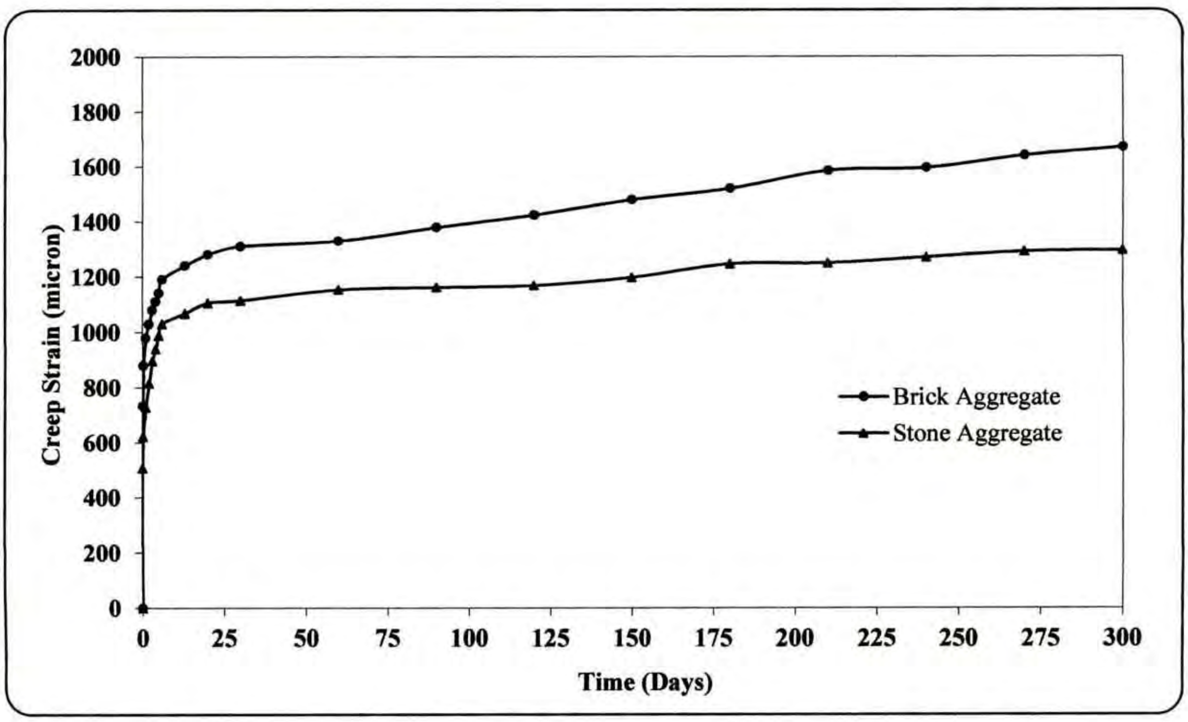

Fig 4.6 Comparison of creep strain for 27.5 MPa concrete loaded at 28th day

Initially, creep strain in brick aggregate concrete is about 45% higher than that of stone aggregate concrete. As the loading age progresses, this difference narrows and at the age of 300^{th} day of loading, becomes approximately 32%. Furthermore, creep strain decreases with increasing strength of concrete. This can be discussed with the simple analogy of water cement ratio. Since, concrete strength is inversely proportional to the water cement ratio and creep is directly proportional to the water cement ratio, the lower the strength the greater the creep. Interestingly, the ratio of this decrease is found to be approximately same for both type of concrete.

Age at which specimen is loaded affect creep strain behavior of initial days of loading only. However, at 300th day of loading, specimens of identical strength show almost same creep strain irrespective of the loading age of 7th or 28th day.

EFFECTIVENESS OF CREEP PREDICITION MODELS FOR CONCRETE MADE OF BRICK CHIPS

5.1 GENERAL

Concrete made of brick chips as coarse aggregate are extensively used in Bangladesh for construction of different types of structures from residential and commercial buildings to medium span bridges. As creep is influenced among many factors including the constituents' materials, relative humidity and temperature, it is essential to see the appropriateness of various creep prediction models for Bangladeshi brick chips made concrete.

In this study, test results derived from concrete specimens having characteristic compressive strength of 17.2, 24.0 and 27.5 N/mm^2 are loaded at 7 days and 28 days are compared with ACI 209 model, CEB-FIP 90 model, B3 model, GL2000 model and Euro code 2 model. The basic aim of this chapter is to examine the effectiveness of these 5 creep prediction models developed and widely used in other countries. Hence this chapter includes the following works.

1. Comparison of experimental creep data with the predicted values obtained from prediction models based on local environment and material.
2. Identification of best creep prediction model in the context of Bangladesh.
3. To propose a modification factor for the best prediction model to achieve creep strains with better accuracy & confidence.

5.2 ANALYSIS TECHNIQUES

Following three basic steps of analysis are followed in order to attain a prediction model of creep for Bangladeshi concrete. Fig 5.1 shows a flow diagram of analysis techniques.

Step 1: **Comparison of Experimental and Predicted Creep Data**

The actual creep coefficients (experimental values) are compared to standard codes and prediction models to evaluate the degree of accuracy of using these prediction models on Bangladeshi concrete. The comparison is done in two ways. Firstly, the actual and predicted creep coefficients/strains are plotted on the same graph to allow comparison graphically. Secondly, the comparison is done by conducting Prediction Model Residuals analysis, which defines whether a model over predicts or under predicts.

Step 2: **Ranking of Prediction Model**

Residual Analysis can be used to identify if a model is over predicting or under predicting but can never be used to identify the best prediction model. In such case, Residual Squared and Error Percentage method can both be used for analyzing experimental data to determine the best prediction model. Residual Squared method is the summation of the residuals squared. A smaller value of both indicates a better fit model.

Step 3: **Modification of the best Prediction Model**

In this stage, a modification factor is developed and proposed to the selected model in order to predict creep and shrinkage more accurately with confidence. Modification factor is developed by correlation method. By this method, the predicted values are plotted against experimental values. The modification factor is taken as the slope of the straight line fitting the data points.

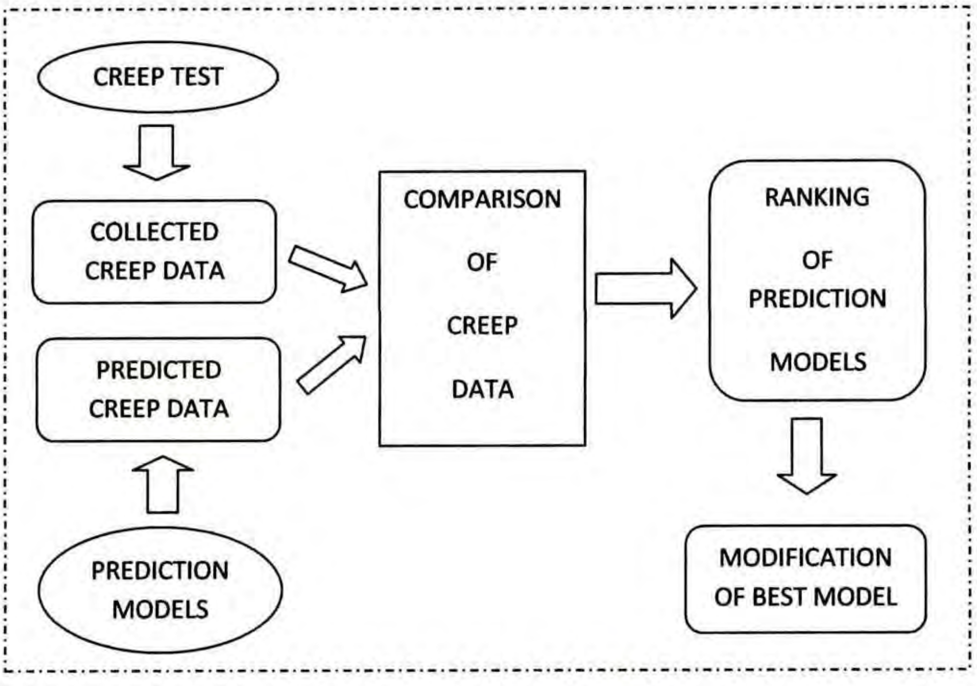

Fig 5.1 Flow diagram of analysis technique

5.3 RESULTS & INTERPRETATIONS

After subsequent testing and data collection as outlined in chapter 3 of this study the following results are obtained.

5.3.1 OVERVIEW OF EXPERIMENTAL RESULTS

Based on the collected data, creep strains up to 300 days for concrete specimens having strength of 17.2, 24.0 and 27.5 N/mm^2 and loaded at 7th and 28th days are shown graphically in Fig 5.2 and Fig 5.3. From these figures, it may be seen that creep of concrete decreases as the strength of concrete increases. For example, for 27.5 N/mm^2 concrete loaded at 7th day, creep strain at 300th day is 1678 micron. This is about 8% less than that of 17.2 N/mm2 concrete loaded at 7th day and at the same loading age of 300 days. Moreover, rate of decrease in creep strain with increasing concrete strength is found to be more or less static up to 200 days from when differences become more pronounced. As an example, for concrete having characteristic strength of 27.5 N/mm^2 and loaded at 7th day have 3% higher creep strain at 300th day than that loaded at 28th day and at the same loading age of 300 days.

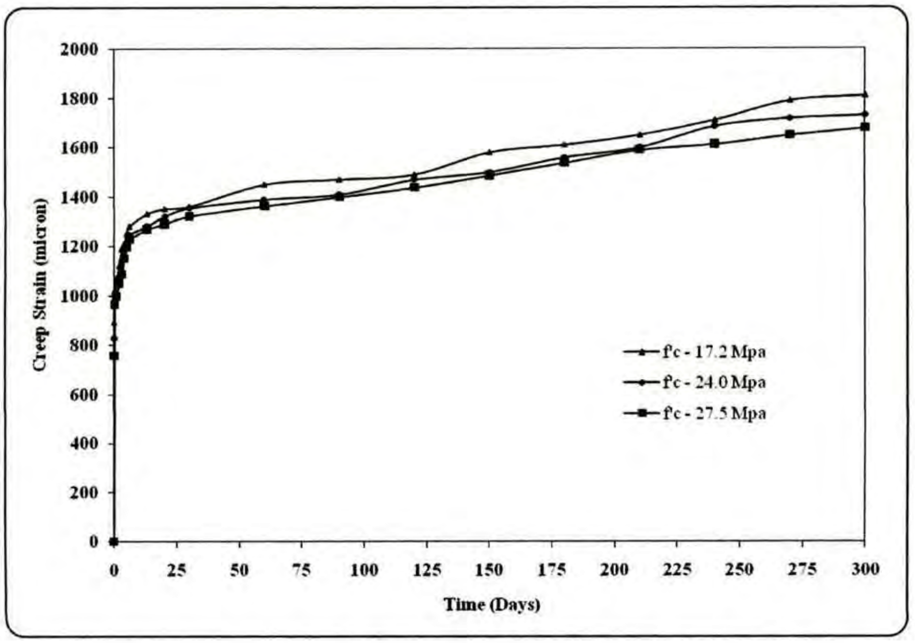

Fig 5.2 Creep strain for specimens loaded at 7th day

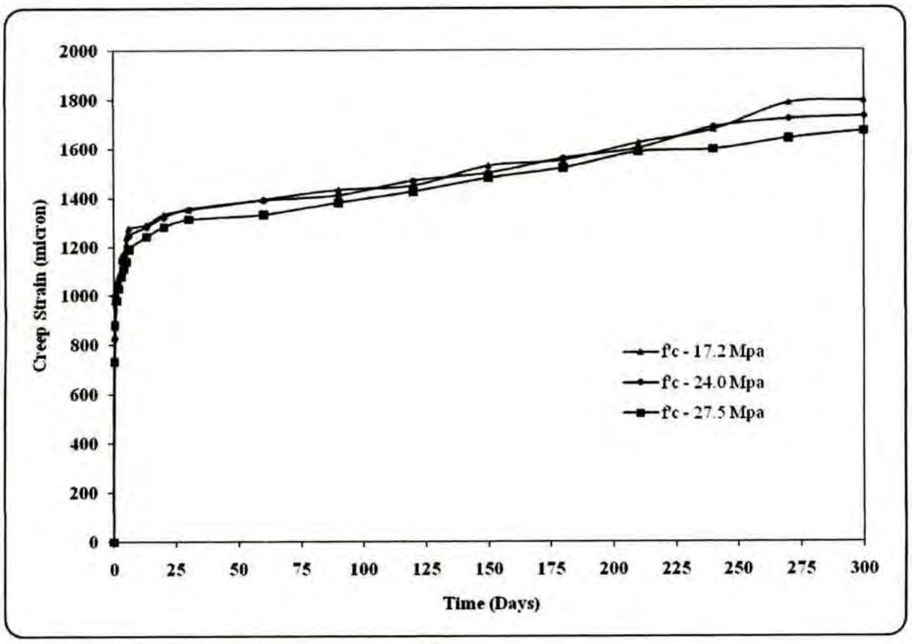

Fig 5.3 Creep strain for specimens loaded at 28th day

5.3.2 COMPARISON OF EXPERIMENTAL & PREDICTED CREEP STRAIN

The comparison of experimental and predicted (example calculations are given in Appendix B) results obtained from ACI 209, CEB-FIP90, B3, GL2000 and Euro code 2 models for concrete of strength 17.2, 24.0 and 27.5 N/mm^2 loaded at both 7th and 28th are shown in from Fig 5.4 through Fig 5.9. For comparison purpose, creep coefficient has been evaluated from experimental results as well as from all the creep prediction models under consideration. Creep coefficient from experimental data was calculated using following formula:

$$\phi_c = \frac{E_c \varepsilon_c}{\sigma} \qquad \text{..} (5.1)$$

Where, ϕ_c = creep coefficient ε_c = Creep Strain

E_c= Modulus of Elasticity of concrete σ = Applied stress

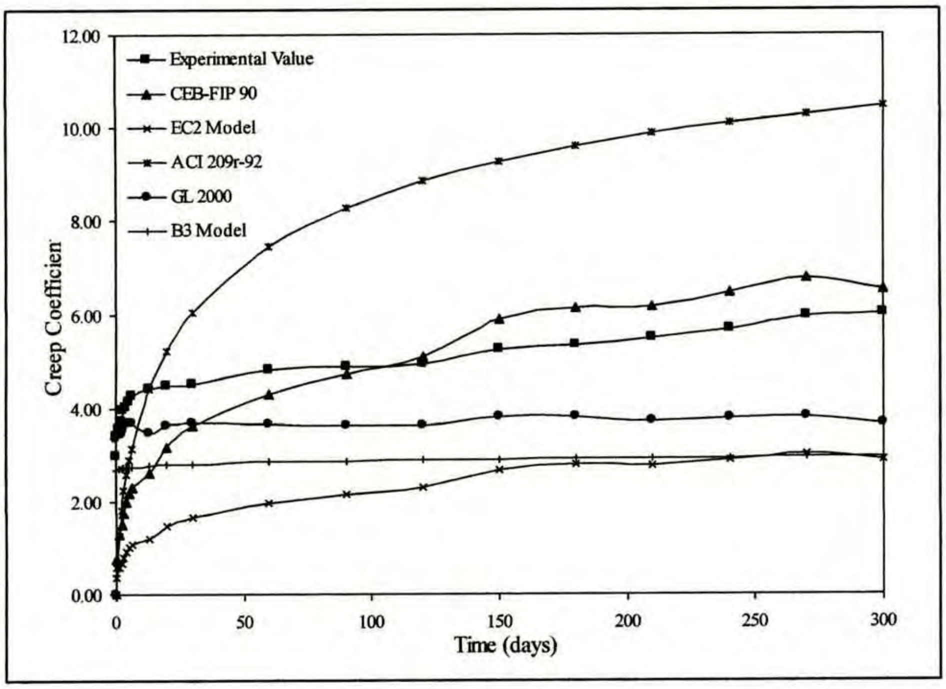

Fig 5.4 Comparison of creep coefficient for 17.2 N/mm^2 concrete loaded at 7th day

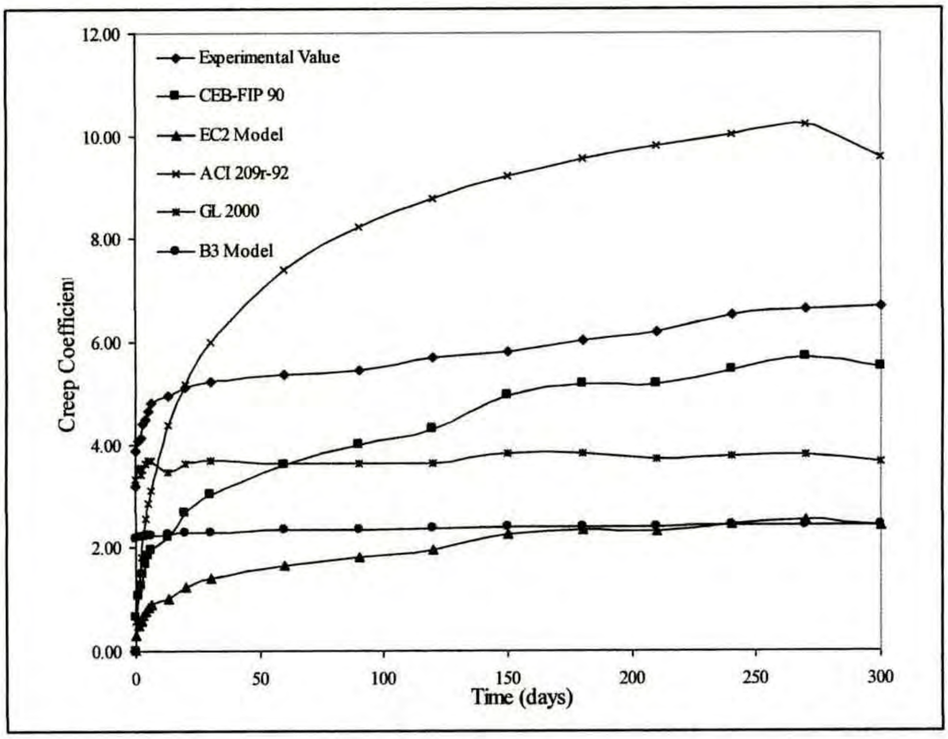

Fig 5.5 Comparison of creep coefficient for 24.0 N/mm^2 concrete loaded at 7th day

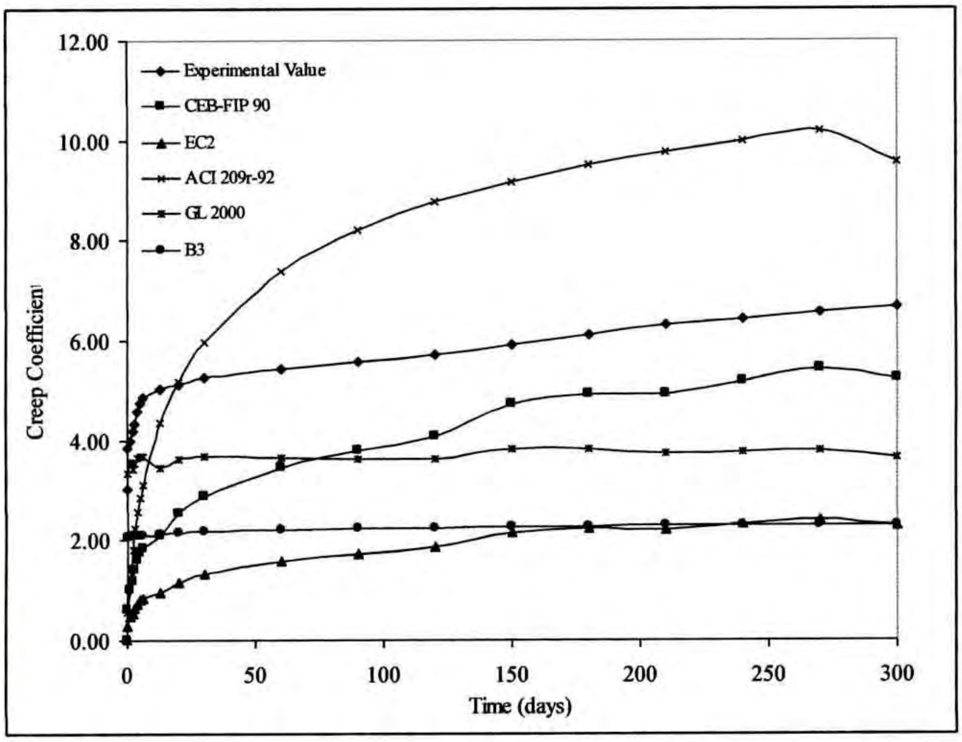

Fig 5.6 Comparison of creep coefficient for 27.5 N/mm^2 concrete loaded at 7th day

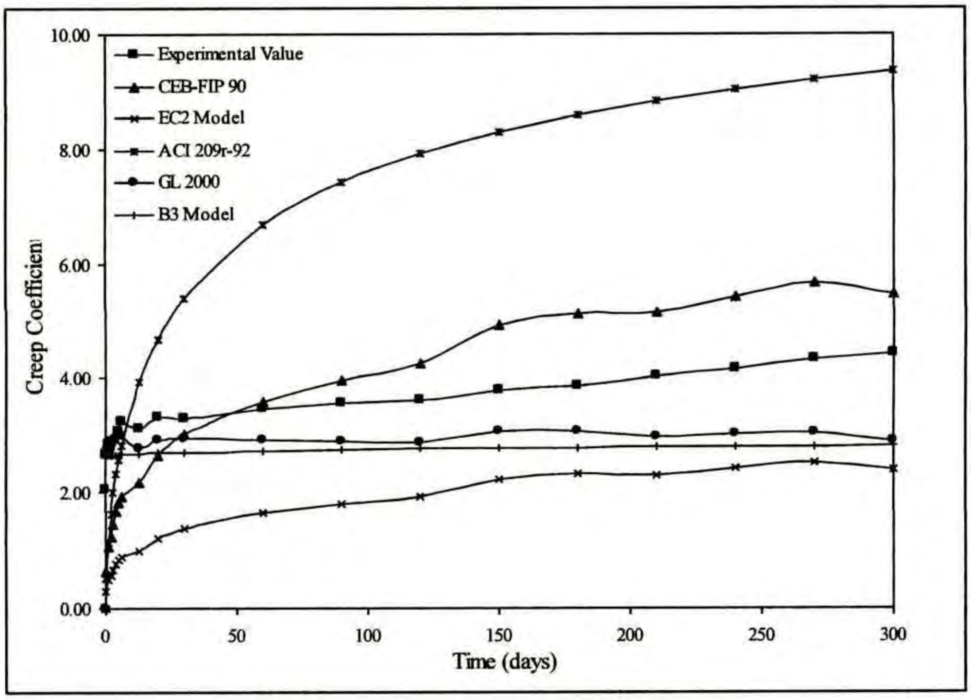

Fig 5.7 Comparison of creep coefficient for 17.2 N/mm^2 concrete loaded at 28th day

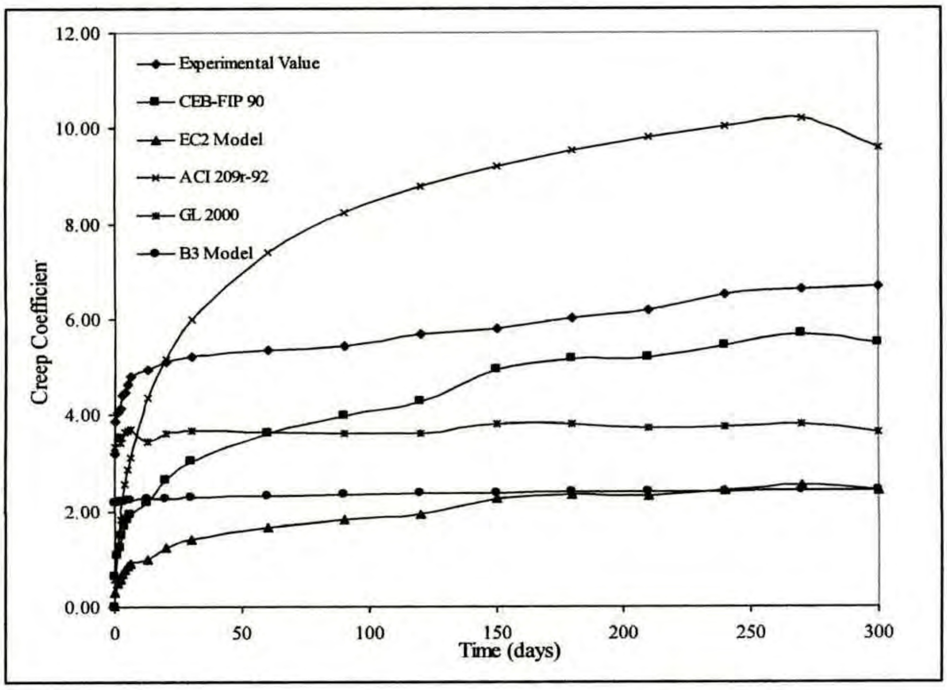

Fig 5.8 Comparison of creep coefficient for 24.0 N/mm^2 concrete loaded at 28th day

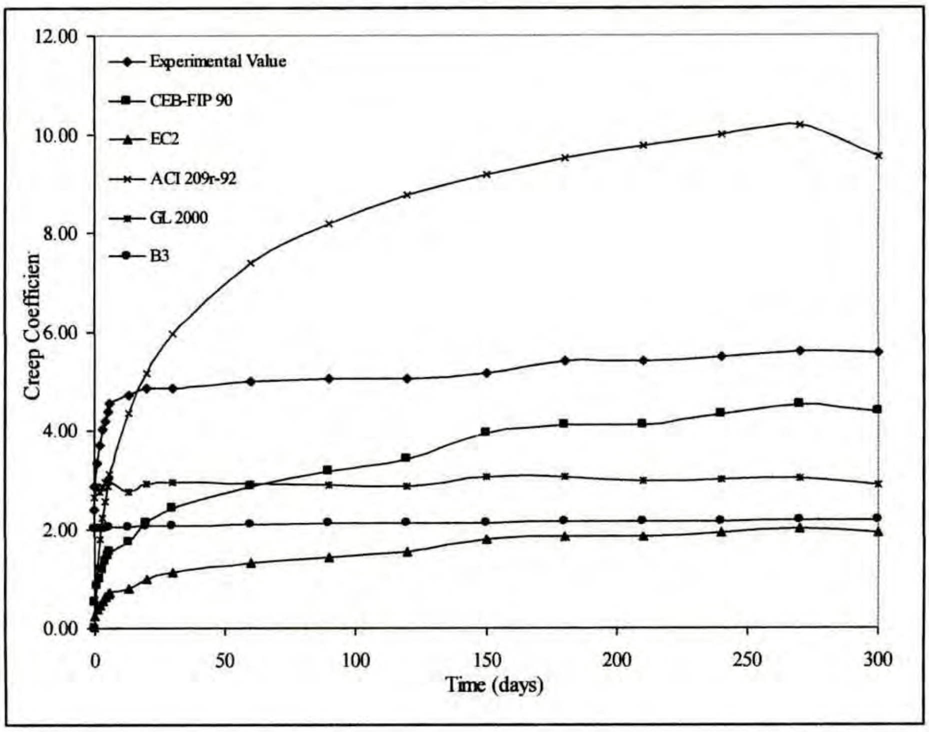

Fig 5.9 Comparison of creep coefficient for 27.5 N/mm^2 concrete loaded at 28th day

As can be seen from these figures, creep coefficient evaluated from the five models examined in this work varies from experimental creep coefficient considerably. Evaluation of creep coefficient from models like ACI 209 gives good approximation of experimental behavior up to 40 days, after that it always over predicts the creep strain. Euro code 2 and B3 model always under predicts the creep deformation and in case of Euro code-2 model, greater deviation from the experimental value is observed. For concrete with relatively low strength (17.2 N/mm^2), CEB-FIP 90 model initially underestimates creep strain after which it overestimates. In case of higher strength concrete (27.5 N/mm^2); it underestimates creep deformation for the entire time period. Initially, GL2000 model shows good agreement with the experimental results for all categories of concrete. After about 20 days it starts to under predict creep strain. However, rate of under prediction in GL 2000 model is far less than what we get from Eurocode2 or B3 model.

5.3.3 RANKING OF PREDICTION MODEL

Among the numerous methods of analyzing experimental data to determine the best prediction models, the residuals squared and error percentage methods are considered here (Kendall, A. et. al., 1973). 'Residual' is the difference between the model and experimental value. Residual is a useful tool to identify whether a prediction model over predicting or under predicting at a given time. Residual squared method is the summation of residuals squared for all data point. The model with the smallest value indicates the best prediction model. On the other hand, percentage difference is calculated as:

$$Percentage\ difference = \frac{Residulal\ x\ 100}{Experimental\ value} \qquad \text{.......................... (5.2)}$$

Average percentage difference for all the date point is evaluated and a smaller percentage difference indicates a better model.

Table 5.1 shows the residual squared and error percentage of creep coefficient for concrete having 17.2, 24.0 and 27.5 N/mm^2 strength loaded at 7th and 28th days. The ranking of prediction models based on residual squared and percentage difference analysis is shown in Table 5.2. Referring to these tables, it may be seen that two different analyses provide almost the same results i.e. deviation from the observed and predicted strain is about the same from the two methods used. Furthermore, as was evident from graphical representation, none of the models give accurate approximation to the observed creep behavior with deviation varying from 15% (GL2000) to as high as 75% (ACI 209 and Euro code 2). For ranking of models, following procedure is used: model that gives the closest result to the observed creep strain is given the first ranking. Subsequent close approximations are ranked as 2, 3 and so on. Raking is done for all three different strength of concrete and for the two age's i.e. 7^{th} and 28^{th} days at which specimens were loaded.

Table 5.1 Residual squared & percentage difference value

Age at Loading (days)	Concrete Strength (N/mm^2)	CEB-FIP 90		EC2 Model		ACI 209r-92		GL 2000		B3 Model	
		% diff.	R squared	% diff.	R squared	% diff.	R squared	% diff.	R squared	% diff.	R squared
7	17.2	30.73	42.94	64.72	163.72	55.13	172.71	20.44	29.46	38.46	75.00
	24	42.03	91.82	73.64	274.79	45.94	131.42	29.40	62.01	55.33	178.68
	27.5	45.17	104.12	75.07	289.53	45.43	128.34	29.75	63.86	57.93	196.33
28	17.2	33.39	27.18	59.75	75.89	74.57	198.55	14.13	9.36	19.54	14.09
	24	43.55	66.59	74.33	203.02	45.72	102.44	32.85	58.73	49.25	110.84
	27.5	48.17	94.34	76.45	237.31	54.54	164.04	36.15	68.64	54.38	138.56

Table 5.2 Overall ranking of prediction models

Age at Loading (days)	Concrete Strength (N/mm^2)	CEB-FIP 90		EC2 Model		ACI 209r-92		GL 2000		B3 Model	
		% diff.	R squared	% diff.	R squared	% diff.	R squared	% diff.	R squared	% diff.	R squared
7	17.2	2	2	5	4	4	5	1	1	3	3
	24	2	2	5	5	3	3	1	1	4	4
	27.5	2	2	5	5	3	3	1	1	4	4
28	17.2	3	3	4	4	5	5	1	1	2	2
	24	2	2	5	5	3	3	1	1	4	4
	27.5	2	2	5	5	4	4	1	1	3	3
	Sum	26		57		45		12		40	
Overall Ranking		2		5		4		1		3	

Finally, all these rankings are summed and the best model is indicated by the lowest value of these summations. From Table 5.2, it may be seen that GL 2000 is the best model to predict creep coefficient for Bangladeshi normal strength concrete whilst CEB-FIP 90 is the second best predictor followed by B3, ACI-209r-92 and EC2 Model.

5.3.4 PROPOSED MODIFICATION OF GL 2000 FOR BRICK CHIPS MADE CONCRETE IN BANGLADESHI ENVIRONMENT

From analysis presented in previous sections, it has been found that none of the model considered in this work accurately predicts the observed creep behavior. Analysis results also show that prediction of GL2000 model was closest among the five models under consideration in this work. However, in order to obtain a more accurate creep behavior using GL 2000, modification is required to the existing equation. For this, a multiplication factor 'α' is derived using correlation method (Kendall, A. et. al., 1973). Fig 5.10, 5.11 and 5.12 represent the correlation for GL2000 model and the experimental values. The slope of the best fit straight line is suggested as the modification factor which is summarized in Table 5.3. From the results presented in Table 5.3, it may be seen that the multiplying factor 'α' to the existing equation of GL 2000 model varies from 1.2 to 1.6, where higher value (1.6) is associated with higher strength concrete (27.5 N/mm^2) and vice versa.

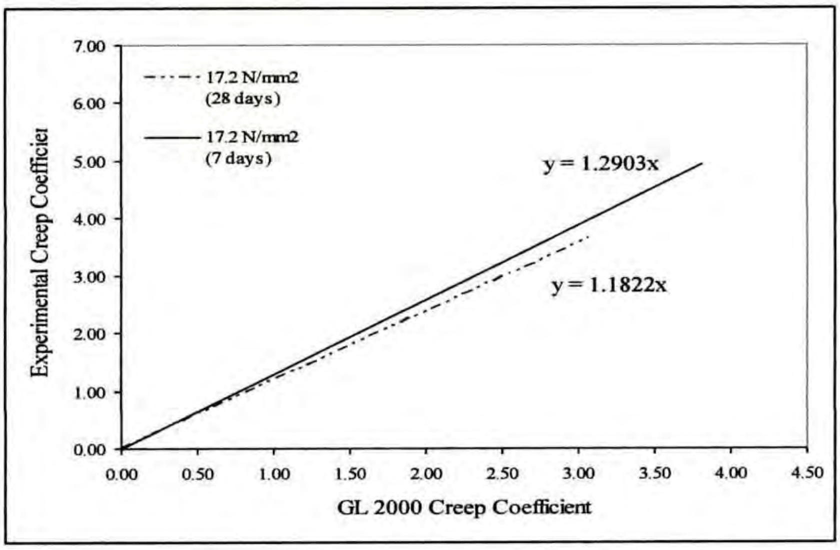

Fig 5.10 Experimental and GL2000 creep coefficient for 17.2 N/mm^2 concrete

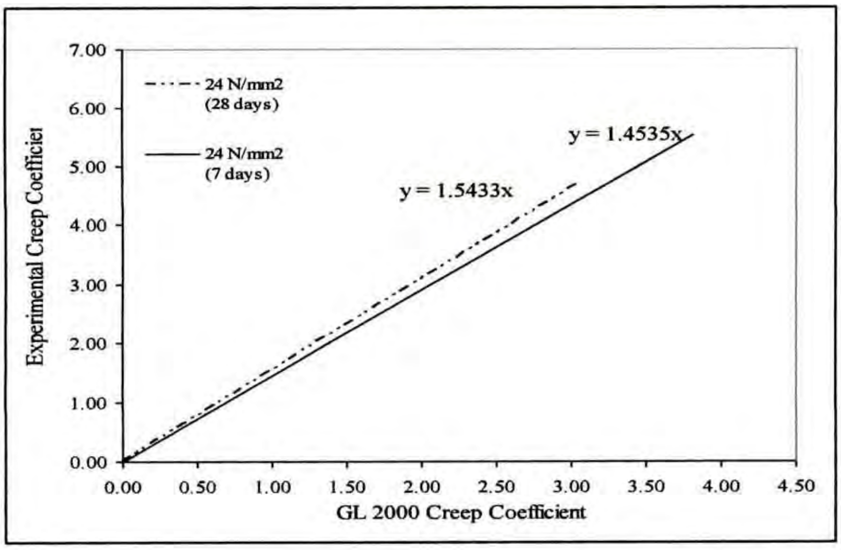

Fig 5.11 Experimental and GL2000 creep coefficient for 24.0 N/mm^2 concrete

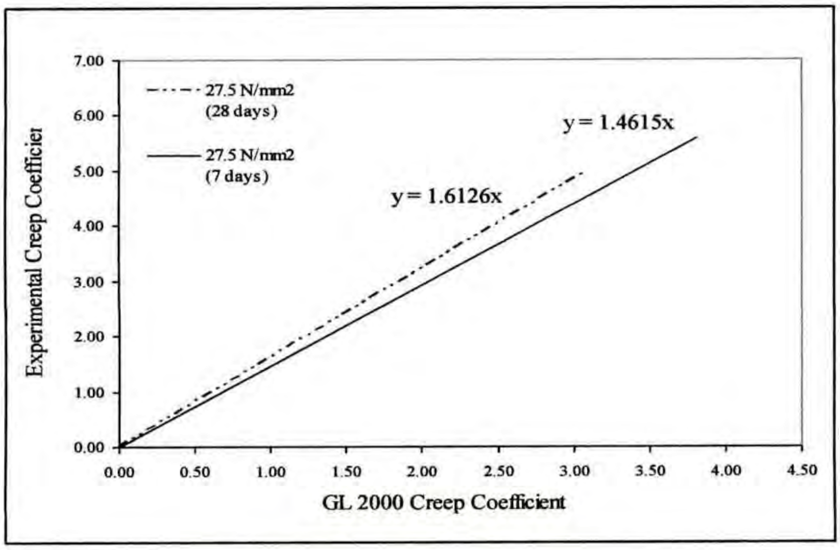

Fig 5.12 Experimental and GL2000 creep coefficient for 27.5 N/mm^2 concrete

Table 5.3 Multiplication factor for creep coefficient (α)

Concrete Strength (N/mm^2)	Age of Loading	
	7 days	28 days
17.2	1.2903	1.1822
24	1.4535	1.5433
27.5	1.4615	1.6126

In this study, several concrete specimens made of brick chips as coarse aggregate in the environment of Bangladesh are prepared and tested for creep behavior as per ASTM C512. Creep strain is measured for up to 300 days. Observed creep behavior is compared with five creep prediction models namely ACI 209, CEB-FIP90, B3, GL2000 and Euro code 2 that are widely used elsewhere. From the analysis it can be seen that none of the models predicts the observed creep behavior accurately. However, comparative study using statistical tools like residual squared and error percentage methods show that GL2000 is the best model that predicts the observed creep strain for brick chips made concrete in Bangladesh with some degree of accuracy. Again, using correlation method, modification factor is proposed for GL 2000, the best predictor model of observed creep behavior. From the analysis, it has been found that a multiplying factor 'α' is required to the existing equation of GL 2000 model where value of 'α' varies from 1.2 to 1.6. It has also been found that as the strength of concrete increases so does the value of 'α' and vice versa whereas a 'α' value of 1.6 is associated with concrete having strength of 27.5 N/mm^2.

CHAPTER 6

CREEP PREDICITION OF CONCRETE MADE OF BRICK CHIPS

6.1 GENERAL

It is evident from chapter 5 that there is a significant difference between the predicted creep from the existing widely used creep prediction models and the experimentally obtained results for concrete made of brick aggregate. The existing models are either over predicting or under predicting the creep of concrete for a hot humid country like Bangladesh. Hence, it is understood that an easy to use creep prediction model will be helpful for design engineers working with brick aggregate concrete. In this context, the objective of this chapter is to formulate an empirical equation to predict creep of concrete using the data found in the experimental work. The model thus derived will be counterchecked by the obtained experimental results. So, this chapter will guide the engineers to predict creep of concrete for a wide range of compressive strength under Bangladeshi environmental conditions.

6.2 EXPERIMENTAL WORK

In addition to the tests outlined in chapter 3, four more concrete specimens made from brick chips aggregate were prepared for four different compressive strength categories. But these specimens were tested for 30 to 50 days rather than 300 days. The creep testing result of these specimens were used in preparing the prediction model along with those tested for 300 days. This is because, the rate of increase or decrease of strain is more pronounced in later days, it is important to manifest their early behaviors in the prediction model with accuracy.

The new concrete specimens were designed for the compressive strength of 18.6, 18.9, 23.4, 28.6 Mpa respectively. Of them specimens having compressive strength of 18.9 and 28.6 Mpa were tested for 50 days whilst the other two were tested for 30 days.

6.2.1 LABORATORY CREEP TEST: RESULT INTERPRETATION

The results of creep test for all specimens obtained from the laboratory test are presented in Fig 6.1-6.7. The new test cylinders were loaded approximately 35% of their ultimate strength keeping all other parameters as before. The new cylinders were loaded at the age of 28 days after casting. Fig 6.1 – 6.7 shows the creep strains of the concrete samples with respect to time. It is found that, creep strain varies with the strength of concrete. The higher the concrete strength the lesser the creep strain and vice versa.

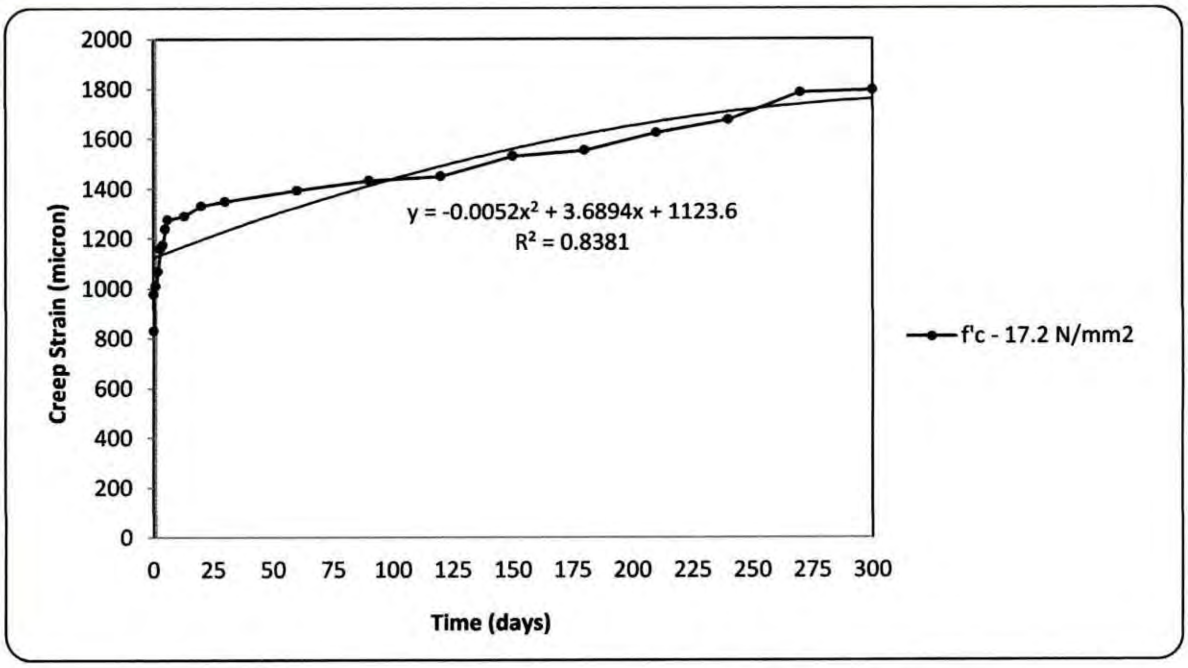

Fig 6.1 Creep strain of concrete prepared for f'c – 17.2 N/mm^2

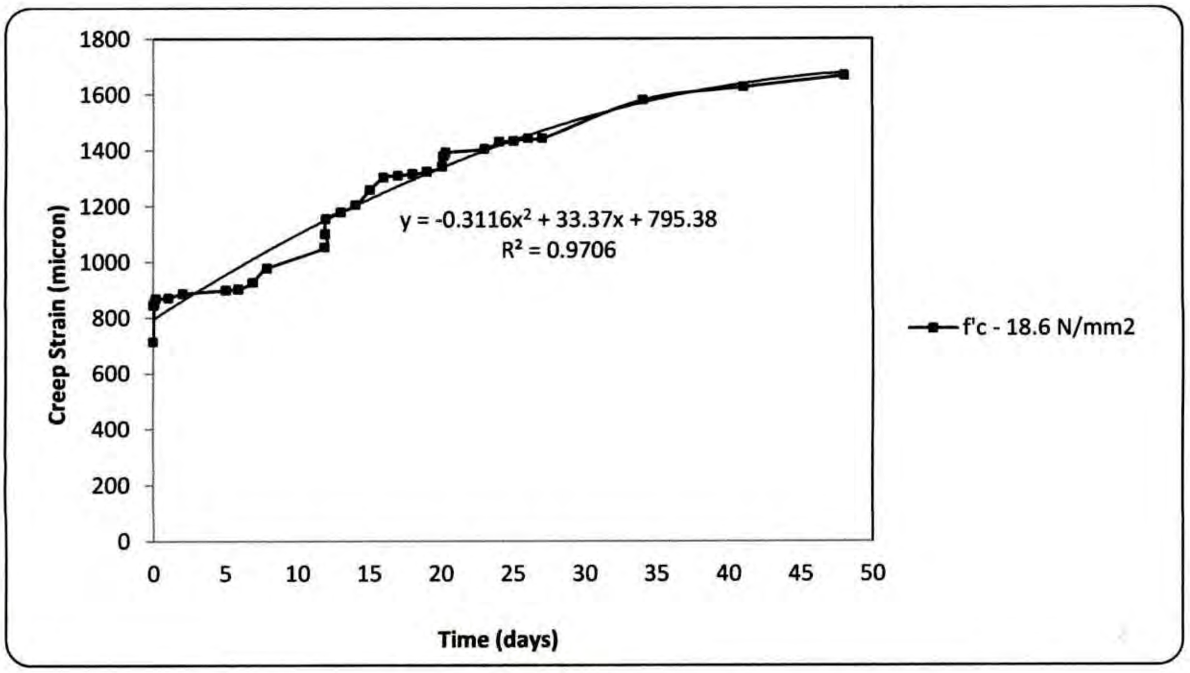

Fig 6.2 Creep strain of concrete prepared for f'c – 18.6 N/mm^2

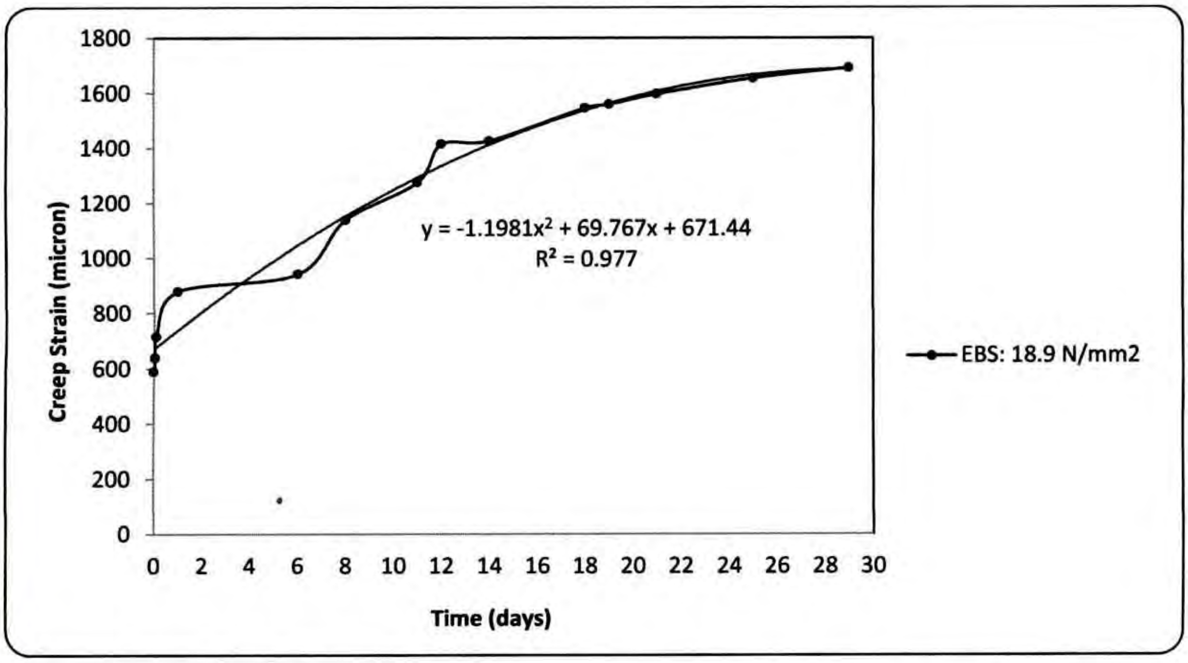

Fig 6.3 Creep strain of concrete prepared for f'c – 18.9 N/mm^2

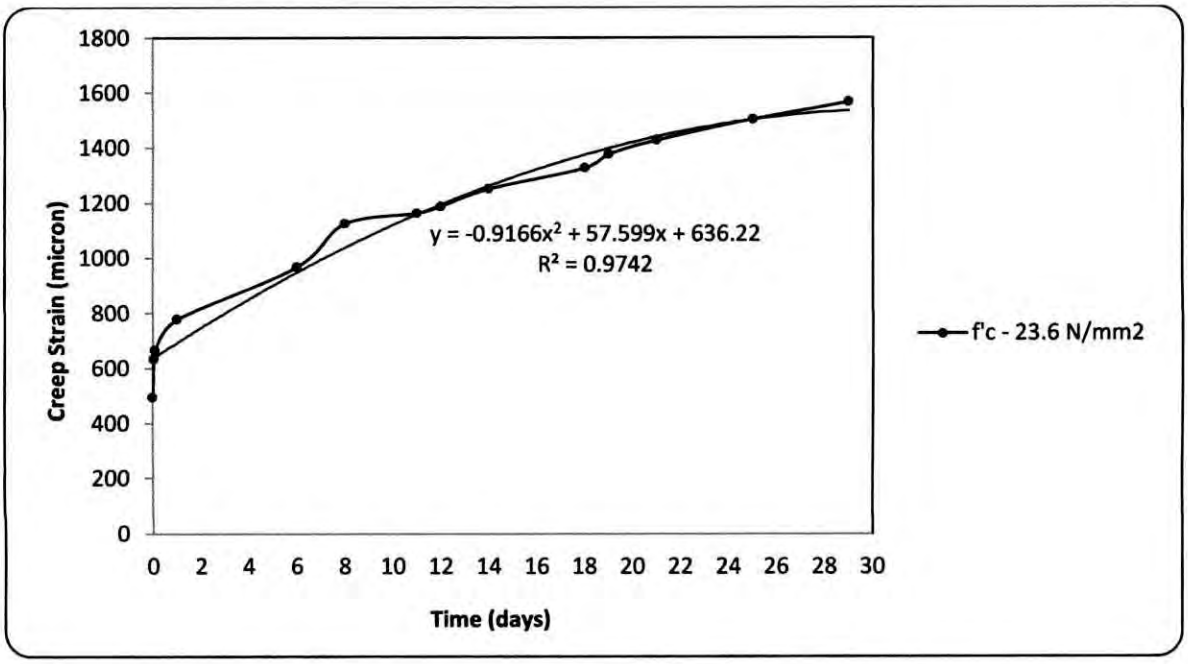

Fig 6.4 Creep strain of concrete prepared for f'c – 23.6 N/mm^2

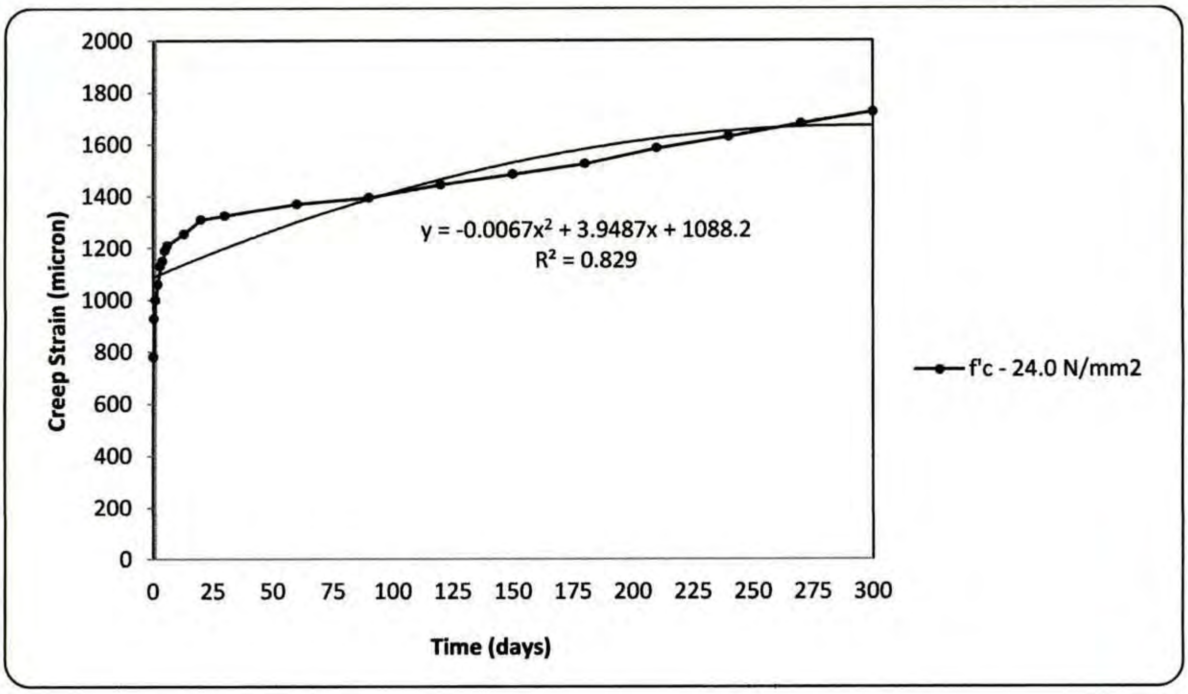

Fig 6.5 Creep strain of concrete prepared for f'c – 24.0 N/mm^2

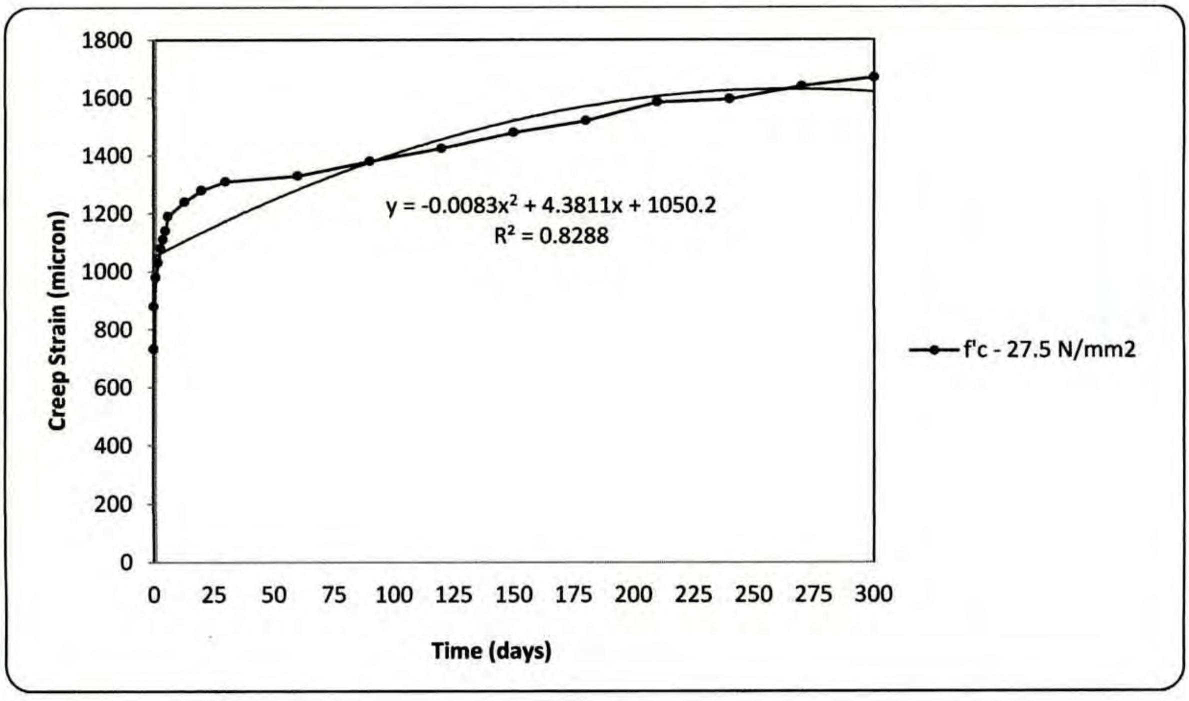

Fig 6.6 Creep strain of concrete prepared for f'c – 27.5 N/mm^2

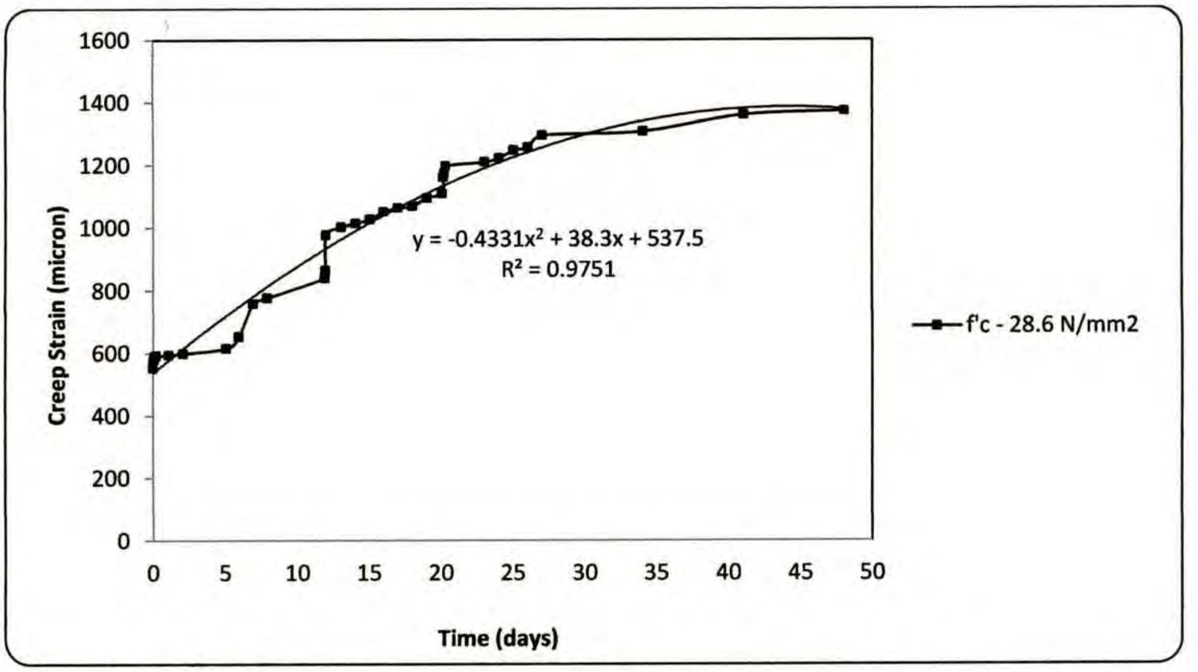

Fig 6.7 Creep strain of concrete prepared for f'c – 28.6 N/mm^2

6.2.2 CREEP EXPRESSIONS: MODEL ESTABLISHMENT

The prime interest of this study is to predict the creep of concrete made from brick chips. Therefore, in this section, the predictions of creep are determined based on the experimentally obtained results using hyperbolic expression. Hyperbolic expression is used in this study because it gives the best fit curve to the experimental results throughout the testing duration.

Fig 6.1- Fig 6.7 shows the creep strain vs. time curve for concrete made from two different aggregate samples. The basic aim of this research is to construct a mathematical model that will represent the creep of concrete having a compressive strength (28 days strength) ranging from 17.2 – 28.6 N/mm^2 under a sustained load of 35% of their respective compressive strength. From the above figures, the following two hyperbolic equations are found.

For, f'c – 17.2 MPa : $y = -0.0052x^2 + 3.6894x + 1123.6$ .... (6.1)

f'c – 18.6 MPa: $y = -0.3116x^2 + 33.37x + 795.4$ .... (6.2)

f'c – 18.9 MPa: $y = -1.198x^2 + 69.767x + 671.4$ .... (6.3)

f'c – 23.6 MPa: $y = -0.9166x^2 + 57.599x + 636.2$ .... (6.4) f'c – 24.0 MPa: $y = -0.0067x^2 + 3.9487x + 1088.2$ .... (6.5)

f'c – 27.5 MPa: $y = -0.0083x^2 + 4.3811x + 1050.2$ .... (6.6)

f'c – 28.6 MPa: $y = -0.4331x^2 + 38.3x + 537.5$ .... (6.7)

Where, y = Creep Strain (Micron)

x = Time (Days)

A hyperbolic relation between creep and time has been suggested by Ross (1937) and Lorman (1940). The creep-time relationship as a hyperbolic function can be written as:

$$Cr = \frac{t}{A+Bt} \qquad \text{.................................. (6.8)}$$

Where, t = Time (Days)

Cr = Creep Strain (Micron)

A, B = Constants

Using equation (6.1) to (6.7), $\frac{t}{Cr}$ vs. t curves for all the three compressive strengths were plotted. Fig 6.8 – 6.14 shows those curves. From those curves, using linear trends, the value of constant 'A' and 'B' can be obtained by simplifying equation (6.8) as following way,

$$\frac{t}{Cr} = A + Bt \qquad \text{................................ (6.9)}$$

Here, the constant 'A' can be termed as residual creep coefficient 'R'. It's unit will be time/strain (days/micron). Constant 'B' can be termed as unit creep coefficient 'U'. Its unit will be strain^{-1} (micron^{-1}). Using the changed notation in above equation we will get,

$$\frac{t}{Cr} = R + Ut \qquad \text{................................ (6.10)}$$

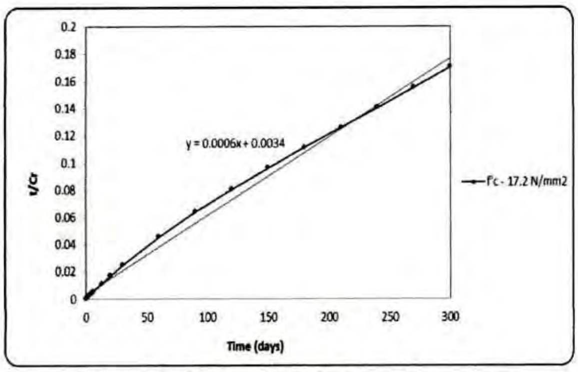

Fig 6.8 t/Cr vs. t for 17.2 grade concrete

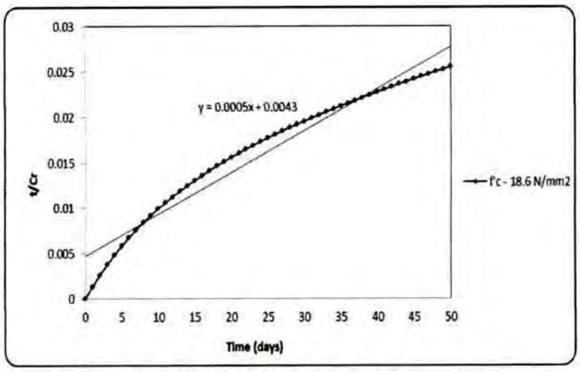

Fig 6.9 t/Cr vs. t for 18.6 grade concrete

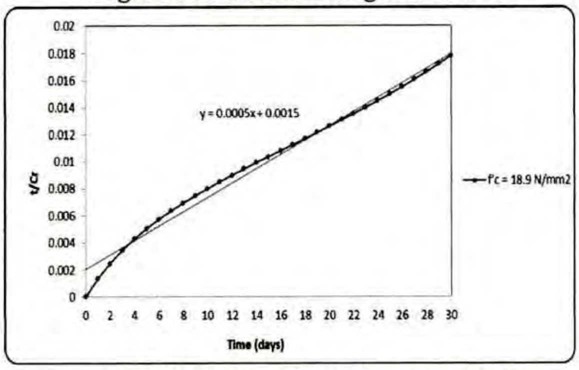

Fig 6.10 t/Cr vs. t for 18.9 grade concrete

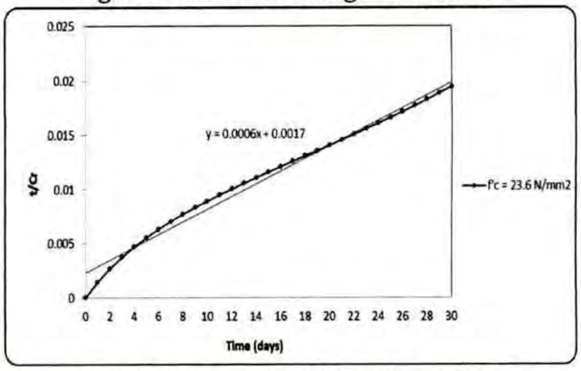

Fig 6.11 t/Cr vs. t for 23.6 grade concrete

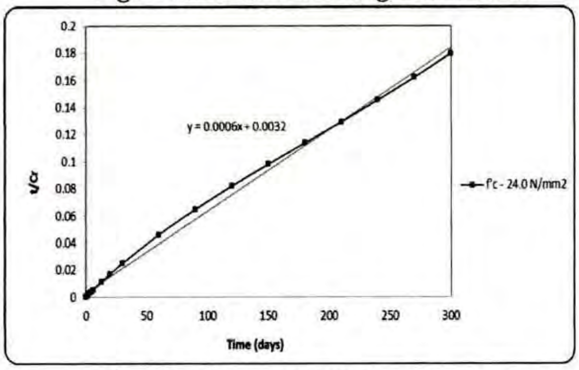

Fig 6.12 t/Cr vs. t for 24.0 grade concrete

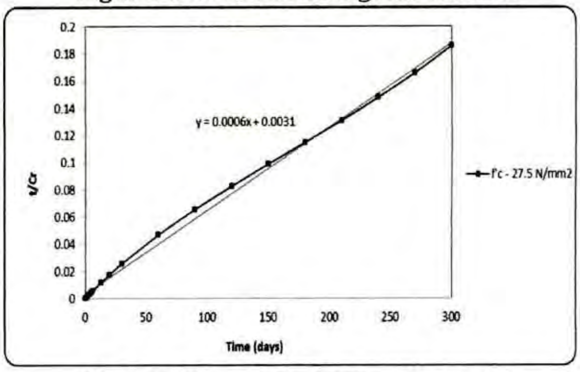

Fig 6.13 t/Cr vs. t for 27.5 grade concrete

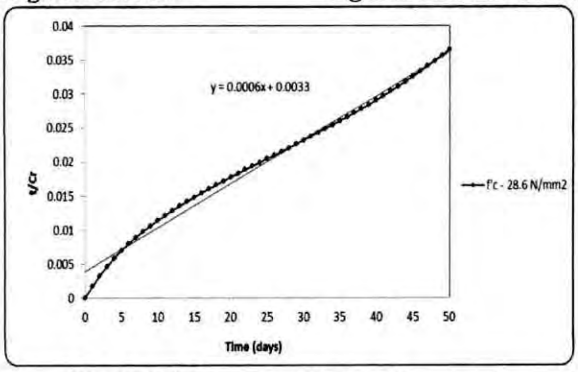

Fig 6.14 t/Cr vs. t for 28.6 grade concrete

From the above figures the linear equations obtained are as follows:

For, $f'c = 17.2$ N/mm^2: $y = 0.0006x + 0.0034$ .... (6.11)

$f'c = 18.6$ N/mm^2: $y = 0.0005x + 0.0043$ .... (6.12)

$f'c = 18.9$ N/mm^2: $y = 0.0005x + 0.0015$ .... (6.13)

$f'c = 23.6$ N/mm^2: $y = 0.0006x + 0.0017$ .... (6.14)

$f'c = 24.0$ N/mm^2: $y = 0.0006x + 0.0032$ .... (6.15)

$f'c = 27.5$ N/mm^2: $y = 0.0006x + 0.0031$ .... (6.16)

$f'c = 28.6$ N/mm^2: $y = 0.0006x + 0.0033$ .... (6.17)

Where, y = t/Cr (Days/micron)

x = t (Days)

Comparing equations (6.11) – (6.17) with equation (6.10), we will get the following tabulated values of 'R' and 'U'

Table 6.1: Values of coefficient 'R' & 'U'

f'c	R	U
17.2	0.0034	0.0006
18.6	0.0043	0.0005
18.9	0.0015	0.0005
23.6	0.0017	0.0006
24.0	0.0032	0.0006
27.5	0.0031	0.0006
28.6	0.0033	0.0006

Using the values tabulated above (Table 6.1) a plot of R vs. Compressive strength and U vs. Compressive strength is plotted. Fig 6.15 – 6.16 shows those plots respectively. For creep prediction of concrete having the compressive strength in the range of 17.2 – 28.6 N/mm^2 these values can be used.

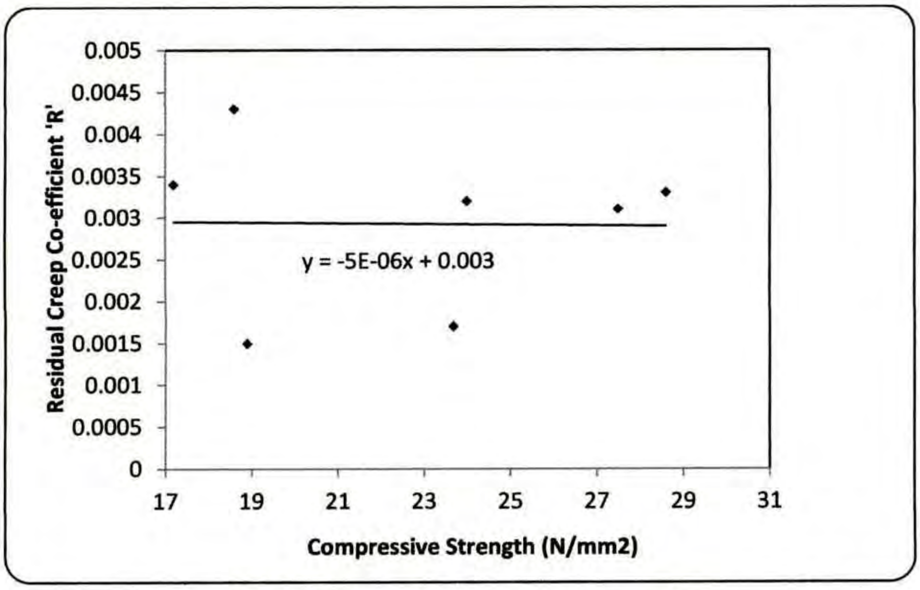

Fig 6.15 R vs. Compressive strength

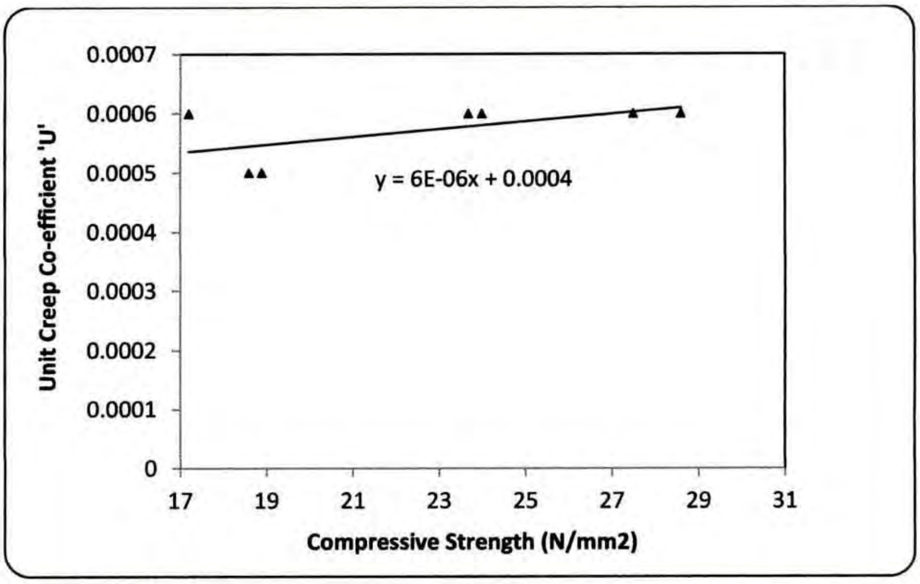

Fig 6.16 U vs. Compressive strength

In order to produce a generalized creep prediction model for concrete made from brick chips, the relationship between compressive strength (f'c) and R or U as obtained from Fig 6.15 & 6.16 can be used. The expressions are as follows:

$R = -5 \times 10^{-06} \times f'c + 0.003$ .... (6.18)

$U = 6 \times 10^{-06} \times f'c + 0.0004$ .... (6.19)

Using these expressions of (6.18) & (6.19) in equation (6.10) it can be written like,

$$Cr = \frac{2 \times 10^5 \times t}{\{(f'c) \times (1.2t - 1) + 40(2t + 15)\}} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (6.20)$$

Where,

Cr = Creep strain (micron)

t = time (days)

f'c = Compressive strength (N/mm^2)

The comparison of strains calculated from the formula with the experimental values for the compressive strength of 17.2 N/mm^2 and 27.5 N/mm^2 is given in Fig 6.17 and Fig 6.18 respectively. Here, the figure clearly indicates that, the theoretical value lies closer to the experimental values which eventually prove that equation is sufficient to compute creep strain of concrete made from brick chips. The predictor equation (6.20) can be used with confidence to predict creep of concrete made from brick chips under hot humid environmental condition for a stress/strength ratio of 0.35.

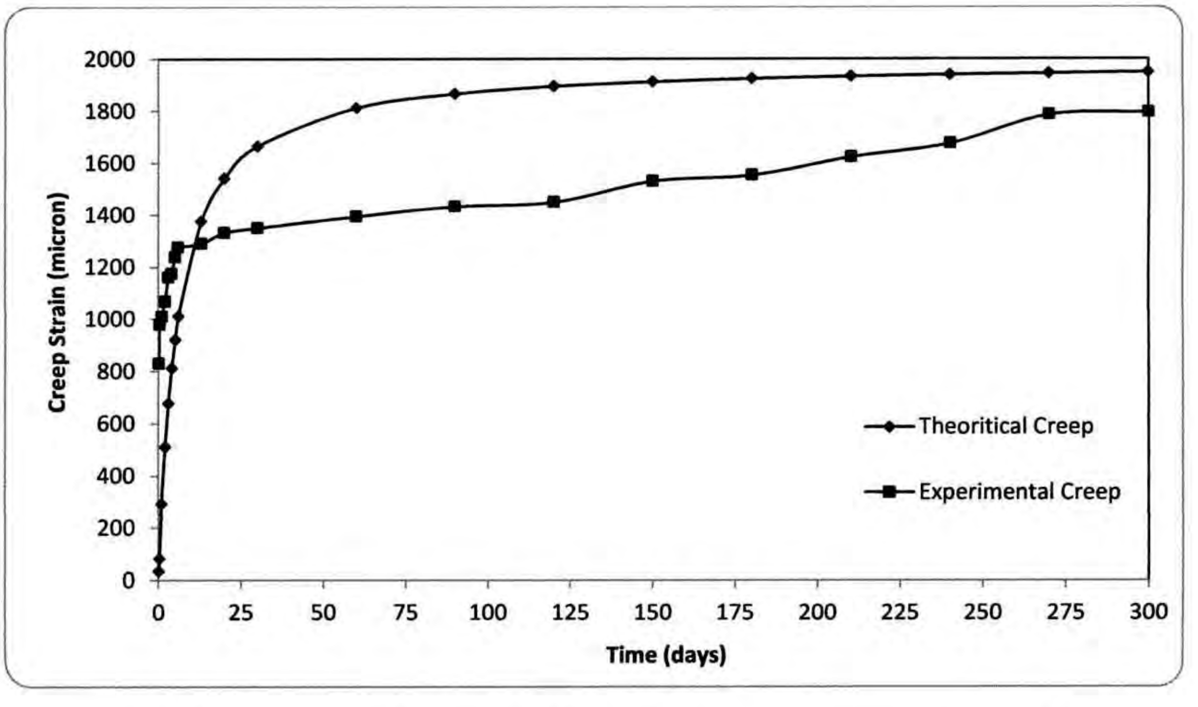

Fig 6.17 Comparison of Theoretical & Experimental creep strain (Grade 17.2)

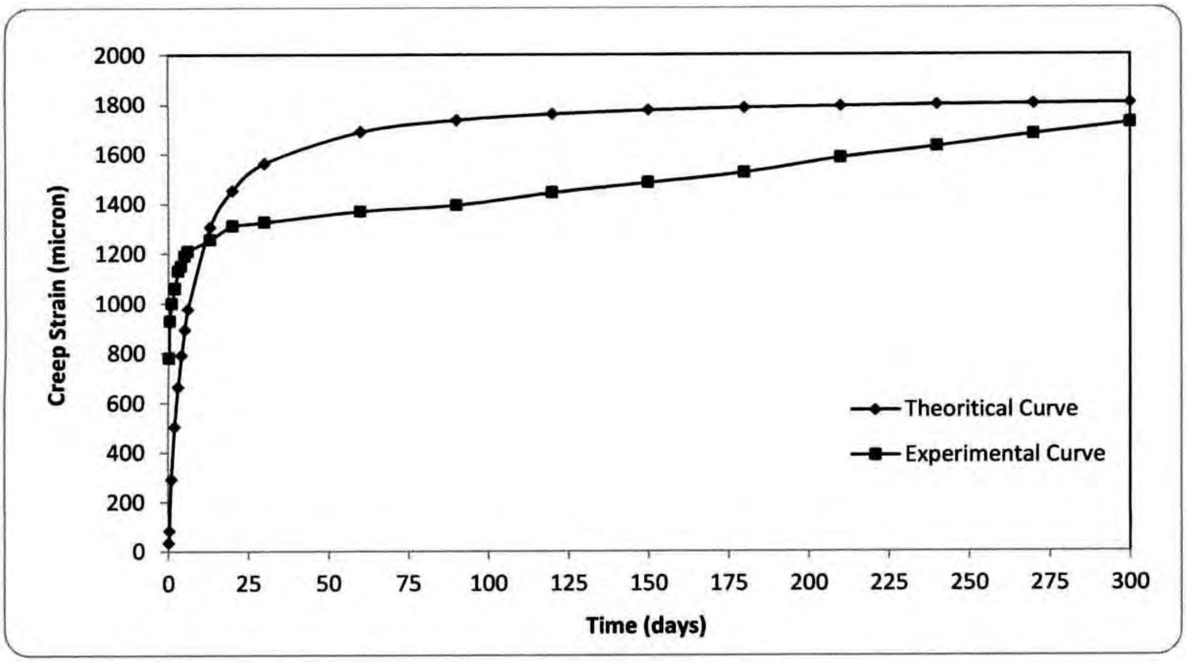

Fig 6.18 Comparison of Theoretical & Experimental creep strain (Grade 24.0)

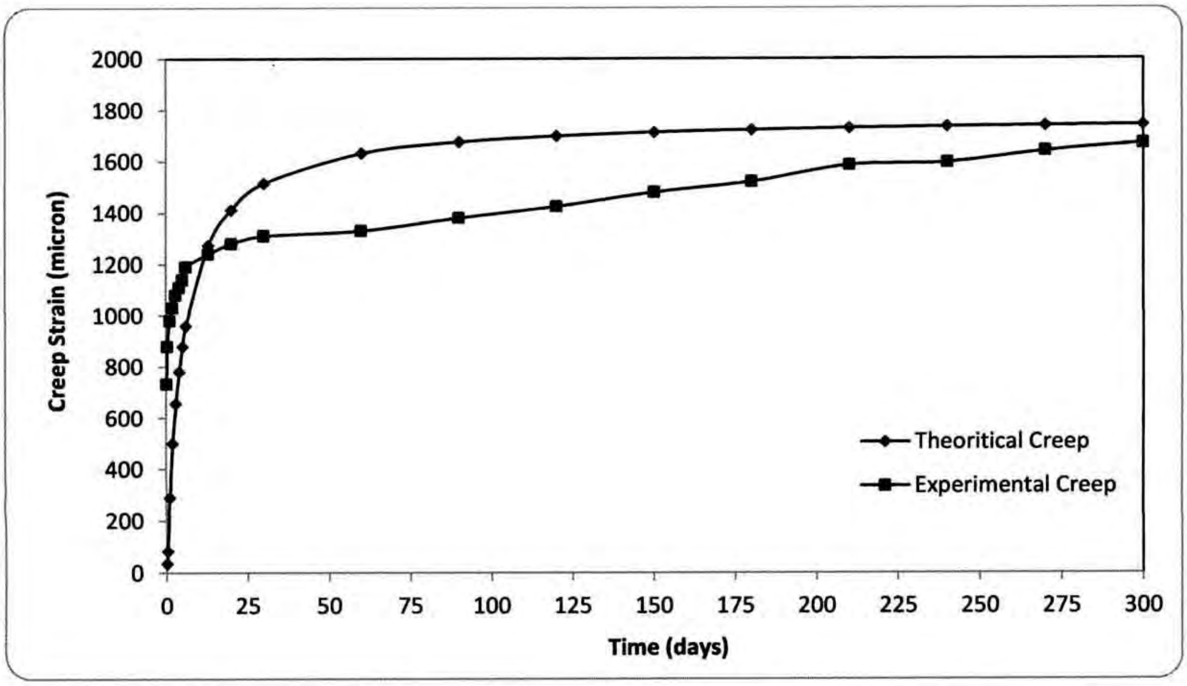

Fig 6.19 Comparison of Theoretical & Experimental creep strain (Grade 27.5)

CHAPTER 7

CONCLUSION AND RECOMMENDATION

7.1 GENERAL

A comprehensive testing plan was taken and executed to understand the creep behavior of concrete made of brick chips. The tests were done conforming to all the standards of ASTM. The creep of brick chips concrete were compared to that of stone chips concrete. Moreover, effectiveness of the widely used creep prediction models was checked against the experimental creep data. Furthermore, an effort had been made to derive mathematical models for determining the creep of concrete made from brick chips.

At the end of all successful tests and analysis described above, the following conclusions can be drawn out.

7.1.1 CREEP COMPARISON OF CONCRETE USING DIFFERENT COARSE AGGREGATE

1. Creep strain of brick chips concrete of same grade is found higher than that of concrete made from stone chips.

2. Creep strain decreases with increase in concrete strength.

3. The ratio of increase is found identical for brick and stone chips concrete irrespective of their grade.

4. Creep strain in brick aggregate concrete is initially 45% higher than that of stone aggregate concrete. However, this difference narrows and at the age of 300^{th} day it becomes approximately 32%.

5. Age at which specimen is loaded affect creep strain behavior of initial days of loading.

7.1.2 EFFECTIVENESS OF VARIOUS CREEP PREDICTION MODELS

1. It is evident from the residual analysis that none of the prediction model is best to predict creep for the entire concrete grade. They are either over predicting or under predicting.

2. From table 5.2 it is found that the GL 2000 model is the best prediction model for creep, while CEB-FIP 90 model is found to be the second best predictor of creep for brick chips concrete under Bangladeshi environment.

3. The percentage of variation from the experimental data to the model value is found as 36.15% for GL 2000, while this value for CEB-FIP 90 model is found as 48.17%. These variations are relatively large but for both the models a variation of 40% is acceptable.

4. A set of modification factors were proposed in Table 5.3. In order to achieve better prediction of creep of brick chips concrete using GL 2000 model under Bangladeshi environment, these values can be used.

7.1.3 CREEP PREDICTION FOR BRICK CHIPS CONCRETE

1. A hyperbolic expression is derived for creep strain of concrete made from brick chips. This expression can be used for the concrete with a wide range of compressive strength for a stress/strength ratio of 0.35.

2. In the process of establishing mathematical model it was observed that the experimental creep strain curve of higher grade concrete resembles with the theoretical creep strain curve up to 200 days.

7.2 RECOMMENDATIONS FOR FUTURE STUDY

1. In future, more batches of different mix to ensure a wide range of compressive strength should be tested. This will not only increase the number of data but also enhance the verification of obtained results.

2. This study thoroughly examines the creep effect of brick chips concrete and proposes mathematical model for creep prediction. The study ends up with suggesting use of GL 2000 model with the modification factor given in Table 5.3 for brick chips concrete under Bangladeshi environment. Further research should be conducted for concrete made of stone chips to obtain the same result for stone chips.

3. The effect of other time dependent phenomena like shrinkage which in turns related to permeability of concrete was not considered while conducting the study. Hence, it is recommended to incorporate these factors in future study to get an actual effect of time dependent phenomena of concrete.

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APPENDIX A

WIDELY USED CREEP PREDICTION MODELS

APPENDIX A

Prediction Model Nomenclature and Equation

EC2 Code Model

Nomenclature

E_c	= Tangent modulus
E_{cm}	= Secant modulus of elasticity of concrete
$\varepsilon_{cc}(\infty, t_o)$	= Creep deformation of concrete at time = ∞ for a constant compressive stress σ_c applied at the age t_o
ε_{cc}	= Creep deformation of concrete
φ	= Creep coefficient
$\varphi_k(\infty, t_o)$	= Non-linear notional creep coefficient
σ_c	= Concrete compressive stress
k_σ	= Stress-strength ratio of $\sigma_c / f_{cm}(t_o)$
$f_{cm}(t_o)$	= Mean concrete compressive strength at the time of loading
f_{cm}	= Mean compressive strength concrete in MPa at the age of 28 days
f_{cmo}	= 10 Mpad
φ_o	= Notional creep coefficient
φ_{RH}	= Factor to allow for the effect of relative humidity on the notional creep coefficient
RH	= Ambient relative humidity (%)
RH_0	=100%
$\beta(f_{cm})$	= Factor to allow for the effect of concrete strength on the notional

creep coefficient

$\beta(t_o)$	= Factor to allow for the effect of concrete age at loading on the notional creep coefficient
h_o	= Notional size of the member (mm)
A_c	= Cross-sectional area
u	= Perimeter of the member in contact with the atmosphere
$\beta_c(t,t_o)$	= Coefficient to describe the development of creep with time after loading
t	= Age of concrete in days at the moment considered
t_o	= Age of concrete at loading in days
$t-t_o$	= Non-adjusted duration of loading in days
t_s	= Age of concrete (days) at the beginning of drying shrinkage
β_H	= Coefficient depending on the relative humidity (RH in %) and notional member size (ho in mm)
$\alpha_{1/2/3}$	= Coefficients to consider the influence of the concrete strength
α	= Power which depends on type of cement
$t_{o,T}$	= Temperature adjusted age of concrete at loading in days
t_T	= Temperature adjusted concrete age which replaces t in the corresponding equations
$T(\Delta t_i)$	= Temperature in ^oC during the time period Δt_i
Δt_i	= Number of days where a temperature T prevails.
ε_{cs}	= Total shrinkage strain
ε_{cd}	= Drying shrinkage strain
ε_{ca}	= Autogenous shrinkage strain
k_h	= Coefficient depending on the notional size h_o

EC2 Model Equations

Creep Strain

$$\varepsilon_{cc}(\infty,t_o)=\varphi(\infty,t_o).(\sigma_c / E_c)$$

$$E_c = 1.05E_{cm}$$

When the compressive stress of concrete at an age to exceed the value $0.45f_{ck}(t_o)$ then creep non-linearity should be considered. In such cases the non-linear notional creep coefficient should be obtained as follow:

$$\varphi_k(\infty,t_o)=\varphi(\infty,t_o)\exp(1.5(k_\sigma - 0.45))$$

Creep coefficient:

$$\varphi(t,t_o)=\varphi_o \cdot \beta_c(t,t_o)$$

$$\varphi_o = \varphi_{RH} \cdot \beta(f_{cm}) \cdot \beta(t_o)$$

$$\varphi_{RH} = 1+\frac{1-RH/100}{0.1\cdot\sqrt[3]{h_o}} \qquad \text{For } f_{cm} \le 35MPA$$

$$\varphi_{RH} = 1+\frac{1-RH/100}{0.1\cdot\sqrt[3]{h_o}}\cdot\alpha_1 \qquad \text{For } f_{cm} \ge 35MPA$$

$$\beta(f_{cm})=\frac{16.8}{\sqrt{f_{cm}}}$$

$$\beta(t_o)=\frac{1}{(0.1+t_o^{\;0.20})}$$

$$h_o = \frac{2A_c}{u}$$

$$\beta_c(t,t_o)=\left[\frac{(t-t_o)}{\beta_H + t - t_o}\right]^{0.3}$$

$$\beta_H = 1.5[1+0.012RH]^{18} h_o + 250 \le 1500 \qquad \text{For } f_{cm} \le 35$$

$$\beta_H = 1.5[1+0.012RH]^{18} h_o + 250\alpha_3 \le 1500\alpha_3 \qquad \text{For } f_{cm} \ge 35$$

$$\alpha_1 = \left(\frac{35}{f_{cm}}\right)^{0.7} \qquad \alpha_2 = \left(\frac{35}{f_{cm}}\right)^{0.2} \qquad \alpha_3 = \left(\frac{35}{f_{cm}}\right)^{0.5}$$

The effect of type of cement may be taken into account by modifying the age of loading t_o

$$t_o = t_{o,T} \cdot \left(\frac{9}{2 + t_{o,T}^{\ 1.2}} + 1\right)^{\alpha} \geq 0.5$$

α = -1 for cement class S

= 0 for cement class N

= 1 for cement class R

The effect of elevated or reduced temperatures within the range 0-80°C on the maturity of concrete

$$t_T = \sum_{i=1}^{n} e^{-(4000/[273+T(\Delta t_i)]-13.65)} \cdot \Delta t_i$$

Shrinkage Strain

$$\varepsilon_{cs} = \varepsilon_{cd} + \varepsilon_{ca}$$

The development of the drying shrinkage strain in time follows from:

$$\varepsilon_{cd}(t) = \beta_{ds}(t, t_s) \cdot k_h \cdot \varepsilon_{cd,0}$$

Values of k_h

h_o	k_h
100	1.0
200	0.85
300	0.75
≥ 500	0.70

$$\beta_{ds}(t,t_s) = \frac{(t-t_s)}{(t-t_s)+0.04\sqrt{h_0^3}}$$

$$\varepsilon_{cd,0} = 0.85\left[(220+110\cdot\alpha_{ds1})\cdot\exp\left(-\alpha_{ds2}\cdot\frac{f_{cm}}{f_{cmo}}\right)\right]\cdot 10^{-6}\cdot\beta_{RH}$$

$$\beta_{RH} = 1.55\left[1-\left(\frac{RH}{RH_o}\right)^3\right]$$

α_{ds1} = 3 for cement Class S

= 4 for cement Class N

= 6 for cement Class R

α_{ds2} = 0.13 for cement Class S

= 0.12 for cement Class N

= 0.11 for cement Class R

$RH_0 = 100\%$

The autogeneous shrinkage strain:

$$\varepsilon_{ca}(t) = \beta_{as}(t)\varepsilon_{ca}(\infty)$$

$$\varepsilon_{ca}(\infty) = 2.5(f_{ck}-10)10^{-6}$$

$$\beta_{as}(t) = 1-\exp(-0.2t^{0.5})$$

ACI 209R-92 Model

Nomenclature

$C_c(t)$	= Creep coefficient at time t
t	= Time after loading (days)
E_{cmto}	= Modulus of elasticity at age of loading
$\varepsilon(t)$	= Total strain; instantaneous plus creep and shrinkage
$\varepsilon_s(t)$	= Shrinkage strain (in/in)
$f'_c(t_o)$	= Mean 28 day compressive strength at age of loading (psi)
f'_{c28}	= Mean 28 day compressive strength (psi)
t_o	= Age of concrete loading (days)
γ	= Unit weight of concrete (Ibs/ft^3)
t_s	= Time after the beginning of shrinkage (days)
Kss	= Shape and size correction factor for shrinkage
K_{SH}	= Relative humidity correction factor for shrinkage
ε_{shu}	= Ultimate shrinkage strain (in./in.)
C_{cu}	= Ultimate creep coefficient
K_{CH}	= Relative humidity correction factor for creep
K_{CA}	= Age at loading correction factor
K_{CS}	= Shape and size correction factor for creep
H	= Relative humidity (%)
V/S	= Volume to surface area ratio (in.)
σ	= Applied stress (psi)
γ_{sc}	= Creep correction factor for slump
s	= Slump (in)
γ_{ac}	= Creep coefficient factor for fine aggregate percentage
γ_{as}	= Shrinkage correction factor for the fine aggregate percentage
ψ	= Fine aggregate percentage (%)
$\gamma_{\alpha c}$	= Creep correction factor for air content
$\gamma_{\alpha s}$	= Shrinkage correction factor for air content
α	= Air content (%)

ACI 209 Equations

Creep compliance function

Compliance function $(\mu\varepsilon / psi) = \frac{1 + C_c(t)}{E_{cmto}}$

Total Strain

$$\varepsilon(t) = \varepsilon_s(t) + \frac{\sigma}{E_{cmto}} * (1 + C_c(t))$$

Compressive Strength

$$f'_c(t_o) = f'_{c(28)} * \left[\frac{t_o}{b + c * t_o} \right]$$

Values of b and c

Type of Cement	Moist Cured Concrete		Steam Cured Concrete	
I	b = 4.0	c = 0.85	b = 1.0	c = 0.95
III	b = 2.3	c = 0.92	b = 0.7	c = 0.98

Note: Estimate not needed. The experimental $f'_c(t_o)$ was used.

Modulus of Elasticity

$$E_{cmto} = 33(\gamma)^{3/2} * \sqrt{f'_c(t_o)}$$

Note: Estimate not needed. The experimental E_{cmto} was used.

Creep strain

Creep strain $= \frac{\sigma}{E_{cmto}} * C_c(t)$

$$C_c(t)=\frac{t^{0.6}}{10+t^{0.6}}*C_{cu}*K_{CH}*K_{CA}*K_{CS}*\gamma_{sc}*\gamma_{ac}*\gamma_{\alpha c}$$

$$C_{cu}=2.35$$

$$K_{CH}=1.27-0.0067*H$$

$$K_{CS}=\frac{2}{3}*\left[1+1.13*e^{(-0.54*V/S)}\right]$$

Value of K_{CA}

Moist Cured Concrete	Steam Cured Concrete
$t,t_o \geq 7$ days, $H \geq 40\%$	$t,t_o \geq 1$ to 3 days, $H \geq 40\%$
$K_{CA} = 1.25\,(t_o)^{-0.118}$	$K_{CA} = 1.13\,(t_o)^{-0.095}$

$\gamma_{sc} = 0.82 + 0.067s$

$\gamma_{ac} = 0.88 + 0.0024\psi$

$\gamma_{\alpha c} = 0.46 + 0.09\alpha$

Shrinkage strain

$$\varepsilon_s(t)=\frac{t_s}{b+t_s}*K_{ss}*K_{SH}*\gamma_{ss}*\gamma_{as}*\gamma_{\alpha s}*\varepsilon_{shu}$$

$$Kss=1.2e^{(-0.12*V/S)}$$

$$\gamma_{ss}=0.89+0.041s$$

For fine aggregate percentage $\leq 50\%$

$$\gamma_{as}=0.30+0.014\psi$$

For fine aggregate percentage $> 50\%$

$$\gamma_{as}=0.90+0.002\psi$$

$$\gamma_{\alpha s}=0.95+0.008\alpha$$

$$\varepsilon_{shu}=780x10^{-6}\,in/in$$

Values of b and K_{SH}

Humidity	Moist Cured Concrete	Steam Cured Concrete
$40\% \leq H \leq 80\%$	b = 35 $t \geq 7$ days	b = 55 $t \geq 1$ to 3 days
	$K_{SH} = 1.4 - 0.01H$	$K_{SH} = 1.4 - 0.01H$
$80\% \leq H \leq 100\%$	b = 35 $t \geq 7$ days	b = 55 $t \geq 1$ to 3 days
	$K_{SH} = 3 - 0.03H$	$K_{SH} = 3 - 0.03H$

CEB-FIP 90 Model

Nomenclature

$\emptyset(t,t_o)$	= Creep coefficient defining creep between time t and t_o
E_c	= Modulus of elasticity at 28 days (N/mm^2)
$E_c(t_o)$	= Modulus of elasticity at age of loading (N/mm^2)
$\varepsilon(t)$	= Total strain; instantaneous plus creep and shrinkage (mm/mm)
$\varepsilon_{cs}(t-t_s)$	= Shrinkage strain between time t and t_s (mm/mm)
t	= Age of concrete after casting (days)
t_s	= Age of concrete at the beginning of shrinkage
f_{cm}	= Mean 28 day concrete compressive strength (N/mm^2)
f_{ck}	= Characteristic compressive strength with 95% confidence (N/mm^2)
t_o	= Age of concrete at loading (days)
$\emptyset_o$	= Notional creep coefficient
$\beta_c(t-t_o)$	= Coefficient describing creep development with time after loading
$\emptyset_{RH}$ coefficient	= Factor to allow for relative humidity on the notional creep ($\emptyset_o$)
$\beta(f_{cm})$	= Factor to allow for effect of concrete strength on the notional creep coefficient ($\emptyset_o$)
$\beta(t_o)$	= Factor to allow for the effect of age of concrete at loading on the notional creep coefficient ($\emptyset_o$)
RH	= Relative humidity (%)
Ac	= Cross-section area of member (mm^2)
u	= Perimeter of member in contact with the atmosphere (mm)
h_o	= $2A_c/u$ = Notional size of member (mm)
β_H	= Coefficient to allow for the effect of relative humidity and the notional member size (h_o) on creep
ε_{cso}	= Notional shrinkage coefficient
$\beta_s(t-t_s)$	= Equation describing development in shrinkage with time
$\varepsilon_c(f_{cm})$	= Factor to allow for the effect of concrete strength on shrinkage
β_{RH}	= Coefficient to allow for the effect of relative humidity on the notional shrinkage coefficient

β_{sc}	= Coefficient depending on type of cement
β_s	= Coefficient to describe the development of shrinkage with time
σ	= Applied stress (N/mm^2)
α	= Coefficient for cement type
$t_{o,T}$	= Temperature adjusted age of concrete at loading (days)
Δt_i	= Number of days at temperature T
$T(\Delta t_i)$	= Temperature during time period Δt_i (^oC)
n	= number of time intervals considered

CEB-FIP 90 Model Code Equations

Total Strain

$$\varepsilon(t) = \varepsilon_{cs}(t - t_s) + \left[\frac{\phi(t, t_o)}{E_c} + \frac{1}{E_c(t_o)}\right]\sigma$$

Mean Concrete Strength

$$f_{cm} = f_{ck} + 8N/mm^2$$

Note: Estimate not needed. The experimental f'_{c28} was used.

Modulus of Elasticity at Age t

$$E_c = 10000\sqrt[3]{f_{cm}}$$

$$E_c(t_o) = (E_c)e^{\left[\frac{S}{2}\left(1-\sqrt{\frac{28}{t}}\right)\right]}$$

		0.28, slow hardeneing cement
S	=	0.25, normal and rapid hardening cement
		0.20, rapid hardening high strength

Note: Estimate not needed. The experimental E_c and $E_c(t_o)$ was used.

Creep Compliance Function

$$\text{Compliance function } [\mu\varepsilon / psi] = \frac{\phi(t, t_o)}{E_c} + \frac{1}{E_c(t_o)}$$

$$\phi(t, t_o) = (\phi_o) * \beta_c(t - t_o)$$

$$\phi_o = \phi_{RH} * \beta(f_{cm}) * \beta(t_o)$$

$$\phi_{RH} = 1 + \frac{\left(1 - \frac{RH}{100}\right)}{0.1 * \sqrt[3]{h_o}}$$

$$\beta(f_{cm}) = \frac{16.8}{\sqrt{f_{cm}}}$$

$$\beta(t_o) = \frac{1}{\left(0.1 + t_o^{0.2}\right)}$$

$$\beta_c(t - t_o) = \frac{(t - t_o)^{0.3}}{\beta_H + (t - t_o)^{0.3}}$$

$$\beta_H = 1.5 * \left[1 + (0.012 + RH)^{18}\right](h_o) + 250 \leq 1500 days$$

The effect of cement type can be modified for the creep coefficient by modifying the age at loading;

$$t_o = t_{o,T} * \left[\frac{9}{2 + \left(t_{o,T}\right)^{1.2}} + 1\right]^{\alpha} \geq 0.5 days$$

$$t_{o,T} = \sum_{i=1}^{n} \Delta t_i * e^{-\left[\frac{4000}{273 + T(\Delta_i)} - 13.65\right]}$$

Values of α

Cement Type	α
SL	-1
N,R	0
RS	1

Shrinkage Strain

$$\varepsilon_{cs}(t - t_s) = \varepsilon_{cso} * \beta_s(t - t_s)$$

$$\varepsilon_{cso} = \varepsilon_s(f_{cm}) * (\beta_{RH})$$

$$\varepsilon_s(f_{cm}) = [160 + \beta_{sc}(90 - f_{cm})] * 10^{-6}$$

Values of β_{sc}

Type of Cement	β_{sc}
Slow hardening (SL)	4
Normal and rapid hardening (N,R)	5
Rapid hardening high strength (RS)	8
Humidity	βRH
40% ≤ RH ≤ 99%, stored in air	-1.55 x βsRH
RH ≥ 99%, immersed in water	0.25

$$\beta_{RH} = 1 - \left(\frac{RH}{100}\right)^3$$

$$\beta_s(t - t_s) = \sqrt{\frac{(t - t_s)}{[0.035 * h_o^2 + (t - t_s)]}}$$

B3 Model

Nomenclature

$J(t,t')$	= Creep compliance function; creep plus elastic (always x 10^{-6}/psi)
α	= Thermal expansion coefficient
$\Delta T(t)$	= Tmperature change from reference at time t
$C_o(t,t')$	= Compliance function for basic creep
$C_d(t,t',t_o)$	= Compliance function for addition creep due to drying
$\varepsilon(t)$	= Total strain; instantaneous plus creep and drying (in/in)
$\varepsilon_{sh}(t)$	= Shrinkage strain (in.in.)
f'_c	= mean 28 day concrete compressive strength (psi)
f_{ck}	= Specified concrete compressive strength at 28 days (psi)
E_{28}	= Modulus of elasticity at 28 days (psi)
q1	= Instantaneous strain due to unit stress
q2	= Aging Visco-elastic compliance
q3	= Non-aging visco-elastic compliance
q4	= Flow compliance
q5	= Creep at drying
t	= Age of concrete after casting
t'	= Age of concrete at loading (days)
t_o	= Age of concrete at the beginning of shrinkage (days)
c	= Cement content of concrete (Ibs/ft^3)
w/c	= Water to cement ratio by weight
a/c	= Aggregate to cement ratio by weight
H(t)	= Spatial average of pore relative humidity within cross section
S(t)	= Time function for shrinkage
$\varepsilon_{sh\infty}$	= Ultimate shrinkage strain (negative, always x10^{-6} in./in.)
w	= Water content of concrete (Ibs/ft^3)
h	= Relative humidity (decimal)
τ_{sh}	= Shrinkage half time (days)
k_s	= cross section shape factor

V/S	= Volume to surface area ratio (in.)
D	= 2(V/S) = Effective cross section thickness (in.)
K_h	= Humidity function for shrinkage

B3 Model Equations

Creep Compliance Function

$$J(t,t')[\mu\varepsilon / psi] = q1 + C_o(t,t') + C_d(t,t',t_o)$$

Total Strain

$$\varepsilon(t) = J(t,t')\sigma + \varepsilon_{sh}(t) + \alpha\Delta T$$

Note: Assume specimens are in thermal equilibrium with room at time of loading.

Mean Compressive Strength

$$f'_c = f_{ck} + 1200$$

Note: Estimate not needed. The experimental f'_c was used.

Elastic Strain and Modulus of Elasticity

$$q1 = \frac{0.6 * 10^6}{E_{28}}$$

$$E_{28} = 57000(f'_c)^{1/2}$$

Note: Estimate not needed. The experimental E_{28} was used.

Basic Creep Compliance

$$C_o(t,t') = q2 + Q(t,t') + q3 * \ln(1 + (t - t')^n + q4 * \ln(t / t')$$

$$Q(t,t') = Q_f(t') * \left[1 + \frac{\left[Q_f(t')^{r(t')}\right]}{\left[Z(t,t')\right]^{r(t')}}\right]^{\frac{-1}{r(t')}}$$

$$Q_f(t') = \left[0.086 * (t')^{2/9} + 1.21 * (t')^{4/9}\right]^{-1}$$

$$Z(t,t') = (t')^{-m} * \ln(1 + (t - t')^n$$

m = 0.5

n = 0.1

$$r(t') = 1.7 * (t')^{0.12} + 8$$

$$q2 = 451.1 * (c)^{0.5} * (f_c')^{-0.9}$$

$$q3 = 0.29 * (w/c)^{4} * q2$$

$$q4 = 0.14 * (a/c)^{-0.7}$$

Drying Creep Compliance

$$C_d(t, t', t_o) = q5[\exp\{-8 * H(t)\} - \exp\{-8 * H(t')\}]^{1/2}$$

$$H(t) = 1 - (1 - h) * S(t)$$

$$H(t') = 1 - (1 - h) * S(t')$$

$$q5 = 5.57x10^{5} * (f'_c)^{-1} * (\varepsilon_{sh\infty})^{-0.6}$$

$$S(t) = \tanh\sqrt{\frac{t - t_o}{\tau_{sh}}}$$

$$S(t') = \tanh\sqrt{\frac{t' - t_o}{\tau_{sh}}}$$

$$\tau_{sh} = K_t (K_s * D)^2$$

$$k_t = 190.8(t_o)^{-0.08} (f'_c)^{-0.25}$$

Values of k_s

Type of Member or Structure	k_s
Infinite slab	1.00
Infinite Cylinder	1.15
Infinite squared prism	1.25
Sphere	1.30
Cube	1.55
Undefined member	1.00

Shrinkage Strain

$$\varepsilon_{sh}(t,t_o) = -\varepsilon_{sh\infty} * k_h * S(t)$$

$$\varepsilon_{sh\infty} = \alpha_1\alpha_2(26(w)^{2.1}(f'_c)^{-0.28} + 270)x10^{-6}$$

$$S(t) = \tanh\sqrt{\frac{t-t_o}{\tau_{sh}}}$$

Values of α_1

Type of Cement	α_1
I	1.00
II	0.85
III	1.10

Values of α_2

Type of Curing	α_2
Steam cured	0.75
water cured or h = 100%	1.00
Sealed during curing	1.20

Values of k_h

Relative Humidity	k_h
for $h \leq 0.98$	$1-h^3$
for h = 1	-0.2
for $0.98 \leq h \leq 1$	use linear interpolation

GL2000 Model

Nomenclature

f_{cm28}	= Mean 28 day concrete compressive strength (psi)
f_{ck28}	= Specified 28 day concrete compressive strength (psi)
t_o	= Age of concrete at loading (days)
K	= Correction term for effect for cement type on shrinkage
E_{cmt}	= Mean modulus of elasticity at age t (psi)
E_{cmto}	= Modulus of elasticity at loading (psi)
f_{cmt}	= Mean concrete compressive strength at age t (psi)
f_{cmto}	= Mean concrete compressive strength at loading (psi)
$f_{cm28(cal)}$	= Compressive strength back calculated from the 28 day modulus of elasticity (psi)
$f_{cm28(average)}$	= Compressive strength from the average of f_{cm28} and $f_{cm28(cal)}$
E_{cm28}	= Mean modulus of elasticity at 28 days (psi)
$E_{cm28(average)}$	= calculated modulus of elasticity from $f_{cm28(average)}$
$Ø(t_c)$	= Correction term for effect of drying before loading
$Ø_{28}$	= Creep coefficient
$J(t,t_o)$	= Creep compliance; creep plus elastic (psi^{-1})
h	= Relative humidity (decimal)
t	= Age of concrete after casting (days)
t_c	= Age of concrete at the beginning of shrinkage (days)
V/S	= Volume to surface area ratio
ε_{sh}	= Shrinkage strain (in./in.)
ε_{shu}	= Ultimate shrinkage strain (in./in.)
$\beta(h)$	= Correction term for effect of humidity on shrinkage
$\beta(t)$	= Correction term for effect of time on shrinkage
f_{cmtc}	= Mean concrete compressive strength at the beginning of shrinkage
$\varepsilon(t)$	= Total strain; instantaneous plus creep and shrinkage (in./in.)

GL2000 Model Equations

Mean Compressive Strength

$f_{cm28} = 1.1 * f_{ck28} + 700$ (in psi)

Note: Only use experimental mean compressive strength is not available.

Mean Compressive Strength Based on Time

$$f_{cmt} = f_{cm28} \frac{t^{3/4}}{(a + b(t))^{3/4}} \quad \text{(in MPa)}$$

Note: Only use if the experimental mean compressive strength at loading is not available.

Values of a, b and k

Cement Type	a	b	k
I	2.8	0.77	1.00
II	3.4	0.72	0.70
III	1	0.92	1.15

Modulus of Elasticity

$E_{cmt} = 500{,}000 + 52{,}000 * \sqrt{f_{cmt}}$ (in psi)

Note: Only use if the experimental modulus is not available.

Mean Compressive Strength from Modulus of Elasticity and Experimental Data

To adjust for aggregate stiffness, adjust the mean compressive strength with the back calculated modulus of elasticity.

Use the experimental E_{cm28} back calculated for f_{cm28} to get $f_{cm28(calc)}$. then average it with experimental f_{cm28} and get the $f_{cm28(average)}$. The $E_{cm28(average)}$ can also be calculated.

$$E_{cm28} = 500{,}000 + 52{,}000 * \sqrt{f_{cm28}}$$

$$f_{cm(average)} = \frac{f_{cm28} + f_{cm28(calc)}}{2}$$

$$E_{cm28(average)} = 500{,}000 + 52{,}000 * \sqrt{f_{cm28(average)}}$$

Creep Strain

$$\phi_{28} =$$

$$\phi(t_c)\left[2\left(\frac{(t-t_c)^{0.3}}{(t-t_c)^{0.3}+14}\right)+\left(\frac{7}{t_o}\right)^{0.5}\left(\frac{t-t_c}{t-t_c+7}\right)^{0.5}+2.5(1-1.086h^2)\left(\frac{t-t_o}{t-t_o+97(V/S)^2}\right)^{0.5}\right]$$

If $t_o = t_c$,

$$\phi(t_c) = 1$$

When $t_o > t_c$

$$\phi(t_c) = \left[1-\left(\frac{t_o - t_c}{t_o - t_c + 97*(V/S)^2}\right)^{0.5}\right]^{0.5}$$

<u>Without experimental data</u>

$$\text{Specific creep} = \frac{\phi_{28}}{E_{cmto}}$$

$$J(t,t_o) = \left[\frac{1+\phi_{28}}{E_{cmto}}\right]$$

$$\text{Creep strain} = \sigma * \left[\frac{\phi_{28}}{E_{cmto}}\right]$$

<u>With experimental data</u>

$$\text{Specific creep} = \frac{\phi_{28}}{E_{cm28(average)}}$$

$$J(t,t_o) = \frac{1}{E_{cmto}} + \frac{\phi_{28}}{E_{cm28(average)}}$$

Creep strain = $\sigma * \frac{\phi_{28}}{E_{cm28(average)}}$

Shrinkage Strain

$$\varepsilon_{sh} = \varepsilon_{shu} * \beta(h) * \beta(t)$$

Values of β(h)

Ambient condition	β(h)
for h < 0.96	1 - 1.18h[4]
for sealed specimen h = 0.96	0

$$\beta(t) = \sqrt{\left(\frac{t - t_c}{t - t_c + 97 * (V/S)^2}\right)}$$

$$\varepsilon_{shu} = 1000 * K * \sqrt{\left(\frac{4350}{f_{cm28}}\right)} x10^{-6}$$

Total Strain

$$\varepsilon(t) = \varepsilon_{sh} + \sigma * \left[\frac{1 + \phi_{28}}{E_{cmto}}\right]$$

If the experimental $E_{c28(average)}$ and E_{cmto} is available then use:

$$\varepsilon(t) = \varepsilon_{sh} + \sigma * \left(\frac{1}{E_{cmto}} + \frac{\phi_{28}}{E_{cm28(average)}}\right)$$

APPENDIX B

EXAMPLE CALCULATIONS OF CREEP PREDICTION MODELS

Example Calculations

Appendix B

Creep prediction of concrete by **CEB-FIP 90 Model**

f_{cm} (N/mm2)	E_c	t (days)	t_o	t-to	S	E_c (to)	Applied Force, lb	Dia (mm)	A_c	Stress, σ (Psi)	u	h_o	RH	φ_{RH}	β_H	$\beta(f_{cm})$	$\beta(t_o)$	$\beta c(t-t_o)$	φ_o	φ (t,to)
24.67	29110.95	19.00	19.00	0.00	0.25	28342.72	27000.00	150.00	17671.44	985.73	471.24	75.00	56.00	2.04	362.50	4.05	0.53	0.00	4.35	0.00
24.67	29110.95	19.25	19.00	0.25	0.25	28370.75	27000.00	150.00	17671.44	985.73	471.24	75.00	58.00	2.00	362.51	4.05	0.53	0.00	4.25	0.77
24.67	29110.95	20.00	19.00	1.00	0.25	28451.83	27000.00	150.00	17671.44	985.73	471.24	75.00	50.00	2.19	362.50	4.05	0.53	0.00	4.65	1.28
24.67	29110.95	21.00	19.00	2.00	0.25	28553.42	27000.00	150.00	17671.44	985.73	471.24	75.00	55.00	2.07	362.50	4.05	0.53	0.00	4.40	1.49
24.67	29110.95	22.00	19.00	3.00	0.25	28648.34	27000.00	150.00	17671.44	985.73	471.24	75.00	51.00	2.16	362.50	4.05	0.53	0.00	4.60	1.76
24.67	29110.95	23.00	19.00	4.00	0.25	28737.28	27000.00	150.00	17671.44	985.73	471.24	75.00	47.00	2.26	362.50	4.05	0.53	0.00	4.81	2.00
24.67	29110.95	24.00	19.00	5.00	0.25	28820.85	27000.00	150.00	17671.44	985.73	471.24	75.00	45.00	2.30	362.50	4.05	0.53	0.00	4.91	2.18
24.67	29110.95	25.00	19.00	6.00	0.25	28899.57	27000.00	150.00	17671.44	985.73	471.24	75.00	45.00	2.30	362.50	4.05	0.53	0.00	4.91	2.31
24.67	29110.95	32.00	19.00	13.00	0.25	29346.92	27000.00	150.00	17671.44	985.73	471.24	75.00	55.00	2.07	362.50	4.05	0.53	0.01	4.40	2.61
24.67	29110.95	39.00	19.00	20.00	0.25	29671.87	27000.00	150.00	17671.44	985.73	471.24	75.00	49.00	2.21	362.50	4.05	0.53	0.01	4.71	3.17
24.67	29110.95	49.00	19.00	30.00	0.25	30012.78	27000.00	150.00	17671.44	985.73	471.24	75.00	48.00	2.23	362.50	4.05	0.53	0.01	4.76	3.61
24.67	29110.95	79.00	19.00	60.00	0.25	30621.33	27000.00	150.00	17671.44	985.73	471.24	75.00	51.00	2.16	362.50	4.05	0.53	0.01	4.60	4.30
24.67	29110.95	109.00	19.00	90.00	0.25	30961.98	27000.00	150.00	17671.44	985.73	471.24	75.00	53.00	2.11	362.50	4.05	0.53	0.01	4.50	4.74
24.67	29110.95	139.00	19.00	120.00	0.25	31187.33	27000.00	150.00	17671.44	985.73	471.24	75.00	54.00	2.09	362.50	4.05	0.53	0.01	4.45	5.11
24.67	29110.95	169.00	19.00	150.00	0.25	31350.64	27000.00	150.00	17671.44	985.73	471.24	75.00	47.00	2.26	362.50	4.05	0.53	0.01	4.81	5.89
24.67	29110.95	199.00	19.00	180.00	0.25	31476.03	27000.00	150.00	17671.44	985.73	471.24	75.00	48.00	2.23	362.50	4.05	0.53	0.01	4.76	6.15
24.67	29110.95	229.00	19.00	210.00	0.25	31576.25	27000.00	150.00	17671.44	985.73	471.24	75.00	52.00	2.14	362.50	4.05	0.53	0.01	4.55	6.16
24.67	29110.95	259.00	19.00	240.00	0.25	31658.75	27000.00	150.00	17671.44	985.73	471.24	75.00	51.00	2.16	362.50	4.05	0.53	0.01	4.60	6.48
24.67	29110.95	289.00	19.00	270.00	0.25	31728.21	27000.00	150.00	17671.44	985.73	471.24	75.00	50.00	2.19	362.50	4.05	0.53	0.01	4.65	6.79
24.67	29110.95	319.00	19.00	300.00	0.25	31787.75	27000.00	150.00	17671.44	985.73	471.24	75.00	56.00	2.04	362.50	4.05	0.53	0.02	4.35	6.55

Creep prediction of concrete by **ACI-209r-92 Model**

Applied Force, lb	Dia, in.	Area, in2	Stress, σ (Psi)	f'c (28) psi	to (days)	b	c	f'c (to)	E_{cmto}	t (days)	Ccu	H	KcH	v/s	Kcs	KcA	s	ψ	α	γ_{sc}	γ_{ac}	$\gamma_{\alpha c}$	Cc (t)
27,000.00	6.00	28.27	954.93	2,580.00	19.00	2.30	0.92	2,478.26	3,018,035.46	0.00	2.35	0.56	1.27	3.00	0.82	0.88	1.50	34.30	3.00	0.92	0.96	0.73	0.00
27,000.00	6.00	28.27	954.93	2,580.00	19.00	2.30	0.92	2,478.26	3,018,035.46	0.25	2.35	0.58	1.27	3.00	0.82	0.88	1.50	34.30	3.00	0.92	0.96	0.73	0.58
27,000.00	6.00	28.27	954.93	2,580.00	19.00	2.30	0.92	2,478.26	3,018,035.46	1.00	2.35	0.50	1.27	3.00	0.82	0.88	1.50	34.30	3.00	0.92	0.96	0.73	1.26
27,000.00	6.00	28.27	954.93	2,580.00	19.00	2.30	0.92	2,478.26	3,018,035.46	2.00	2.35	0.55	1.27	3.00	0.82	0.88	1.50	34.30	3.00	0.92	0.96	0.73	1.82
27,000.00	6.00	28.27	954.93	2,580.00	19.00	2.30	0.92	2,478.26	3,018,035.46	3.00	2.35	0.51	1.27	3.00	0.82	0.88	1.50	34.30	3.00	0.92	0.96	0.73	2.25
27,000.00	6.00	28.27	954.93	2,580.00	19.00	2.30	0.92	2,478.26	3,018,035.46	4.00	2.35	0.47	1.27	3.00	0.82	0.88	1.50	34.30	3.00	0.92	0.96	0.73	2.59
27,000.00	6.00	28.27	954.93	2,580.00	19.00	2.30	0.92	2,478.26	3,018,035.46	5.00	2.35	0.45	1.27	3.00	0.82	0.88	1.50	34.30	3.00	0.92	0.96	0.73	2.89
27,000.00	6.00	28.27	954.93	2,580.00	19.00	2.30	0.92	2,478.26	3,018,035.46	6.00	2.35	0.45	1.27	3.00	0.82	0.88	1.50	34.30	3.00	0.92	0.96	0.73	3.14
27,000.00	6.00	28.27	954.93	2,580.00	19.00	2.30	0.92	2,478.26	3,018,035.46	13.00	2.35	0.55	1.27	3.00	0.82	0.88	1.50	34.30	3.00	0.92	0.96	0.73	4.41
27,000.00	6.00	28.27	954.93	2,580.00	19.00	2.30	0.92	2,478.26	3,018,035.46	20.00	2.35	0.49	1.27	3.00	0.82	0.88	1.50	34.30	3.00	0.92	0.96	0.73	5.22
27,000.00	6.00	28.27	954.93	2,580.00	19.00	2.30	0.92	2,478.26	3,018,035.46	30.00	2.35	0.48	1.27	3.00	0.82	0.88	1.50	34.30	3.00	0.92	0.96	0.73	6.03
27,000.00	6.00	28.27	954.93	2,580.00	19.00	2.30	0.92	2,478.26	3,018,035.46	60.00	2.35	0.51	1.27	3.00	0.82	0.88	1.50	34.30	3.00	0.92	0.96	0.73	7.47
27,000.00	6.00	28.27	954.93	2,580.00	19.00	2.30	0.92	2,478.26	3,018,035.46	90.00	2.35	0.53	1.27	3.00	0.82	0.88	1.50	34.30	3.00	0.92	0.96	0.73	8.29
27,000.00	6.00	28.27	954.93	2,580.00	19.00	2.30	0.92	2,478.26	3,018,035.46	120.00	2.35	0.54	1.27	3.00	0.82	0.88	1.50	34.30	3.00	0.92	0.96	0.73	8.86
27,000.00	6.00	28.27	954.93	2,580.00	19.00	2.30	0.92	2,478.26	3,018,035.46	150.00	2.35	0.47	1.27	3.00	0.82	0.88	1.50	34.30	3.00	0.92	0.96	0.73	9.28
27,000.00	6.00	28.27	954.93	2,580.00	19.00	2.30	0.92	2,478.26	3,018,035.46	180.00	2.35	0.48	1.27	3.00	0.82	0.88	1.50	34.30	3.00	0.92	0.96	0.73	9.61
27,000.00	6.00	28.27	954.93	2,580.00	19.00	2.30	0.92	2,478.26	3,018,035.46	210.00	2.35	0.52	1.27	3.00	0.82	0.88	1.50	34.30	3.00	0.92	0.96	0.73	9.87
27,000.00	6.00	28.27	954.93	2,580.00	19.00	2.30	0.92	2,478.26	3,018,035.46	240.00	2.35	0.51	1.27	3.00	0.82	0.88	1.50	34.30	3.00	0.92	0.96	0.73	10.10
27,000.00	6.00	28.27	954.93	2,580.00	19.00	2.30	0.92	2,478.26	3,018,035.46	270.00	2.35	0.50	1.27	3.00	0.82	0.88	1.50	34.30	3.00	0.92	0.96	0.73	10.29
27,000.00	6.00	28.27	954.93	2,580.00	19.00	2.30	0.92	2,478.26	3,018,035.46	300.00	2.35	0.56	1.27	3.00	0.82	0.88	1.50	34.30	3.00	0.92	0.96	0.73	10.45

Example Calculations

Appendix B

Creep prediction of concrete by **EC 2 Model**																					
f_{cm} (MPa)	$\beta(f_{cm})$	Dia (mm)	A_c	u	h_o	RH	α_1	α_2	α_3	α=-1,0,1	φ_{RH} when fcm<=35 MPA	t (days)	$t_{o,T}$ (days)	t_o	$t-t_o$	β_H when fcm<=35 MPA	Final, β_H when fcm<=35 MPA	$\beta(t_o)$	$\beta_c(t,t_o)$	φ_o when fcm<=35 MPA	$\varphi(t,t_o)$ when fcm<=35 MPA
17.20	4.05	150.00	17671.44	942.48	37.50	56.00	1.64	1.15	1.43	0.00	2.31	19.00	19.00	19.00	0.00	586895.09	1500.00	0.53	0.00	4.93	0.00
17.20	4.05	150.00	17671.44	942.48	37.50	58.00	1.64	1.15	1.43	0.00	2.25	19.25	19.00	19.00	0.25	758457.00	1500.00	0.53	0.07	4.80	0.35
17.20	4.05	150.00	17671.44	942.48	37.50	50.00	1.64	1.15	1.43	0.00	2.49	20.00	19.00	19.00	1.00	265883.11	1500.00	0.53	0.11	5.31	0.59
17.20	4.05	150.00	17671.44	942.48	37.50	55.00	1.64	1.15	1.43	0.00	2.34	21.00	19.00	19.00	2.00	515559.46	1500.00	0.53	0.14	4.99	0.68
17.20	4.05	150.00	17671.44	942.48	37.50	51.00	1.64	1.15	1.43	0.00	2.46	22.00	19.00	19.00	3.00	304123.76	1500.00	0.53	0.15	5.25	0.81
17.20	4.05	150.00	17671.44	942.48	37.50	47.00	1.64	1.15	1.43	0.00	2.58	23.00	19.00	19.00	4.00	176603.47	1500.00	0.53	0.17	5.50	0.93
17.20	4.05	150.00	17671.44	942.48	37.50	45.00	1.64	1.15	1.43	0.00	2.64	24.00	19.00	19.00	5.00	133754.38	1500.00	0.53	0.18	5.63	1.02
17.20	4.05	150.00	17671.44	942.48	37.50	45.00	1.64	1.15	1.43	0.00	2.64	25.00	19.00	19.00	6.00	133754.38	1500.00	0.53	0.19	5.63	1.07
17.20	4.05	150.00	17671.44	942.48	37.50	55.00	1.64	1.15	1.43	0.00	2.34	32.00	19.00	19.00	13.00	515559.46	1500.00	0.53	0.24	4.99	1.20
17.20	4.05	150.00	17671.44	942.48	37.50	49.00	1.64	1.15	1.43	0.00	2.52	39.00	19.00	19.00	20.00	232219.82	1500.00	0.53	0.27	5.37	1.47
17.20	4.05	150.00	17671.44	942.48	37.50	48.00	1.64	1.15	1.43	0.00	2.55	49.00	19.00	19.00	30.00	202614.52	1500.00	0.53	0.31	5.44	1.67
17.20	4.05	150.00	17671.44	942.48	37.50	51.00	1.64	1.15	1.43	0.00	2.46	79.00	19.00	19.00	60.00	304123.76	1500.00	0.53	0.38	5.25	1.97
17.20	4.05	150.00	17671.44	942.48	37.50	53.00	1.64	1.15	1.43	0.00	2.40	109.00	19.00	19.00	90.00	396730.58	1500.00	0.53	0.42	5.12	2.16
17.20	4.05	150.00	17671.44	942.48	37.50	54.00	1.64	1.15	1.43	0.00	2.37	139.00	19.00	19.00	120.00	452472.60	1500.00	0.53	0.46	5.06	2.32
17.20	4.05	150.00	17671.44	942.48	37.50	47.00	1.64	1.15	1.43	0.00	2.58	169.00	19.00	19.00	150.00	176603.47	1500.00	0.53	0.49	5.50	2.68
17.20	4.05	150.00	17671.44	942.48	37.50	48.00	1.64	1.15	1.43	0.00	2.55	199.00	19.00	19.00	180.00	202614.52	1500.00	0.53	0.51	5.44	2.78
17.20	4.05	150.00	17671.44	942.48	37.50	52.00	1.64	1.15	1.43	0.00	2.43	229.00	19.00	19.00	210.00	347522.97	1500.00	0.53	0.53	5.18	2.76
17.20	4.05	150.00	17671.44	942.48	37.50	51.00	1.64	1.15	1.43	0.00	2.46	259.00	19.00	19.00	240.00	304123.76	1500.00	0.53	0.55	5.25	2.90
17.20	4.05	150.00	17671.44	942.48	37.50	50.00	1.64	1.15	1.43	0.00	2.49	289.00	19.00	19.00	270.00	265883.11	1500.00	0.53	0.57	5.31	3.02
17.20	4.05	150.00	17671.44	942.48	37.50	56.00	1.64	1.15	1.43	0.00	2.31	319.00	19.00	19.00	300.00	586895.09	1500.00	0.53	0.58	4.93	2.88

Creep prediction of concrete by **GL 2000 Model**												
fcmt (N/mm2)	Ecmt	to	tc	to-tc	V/S	φtc	t	t-tc	φ28	h	t-to	Creep Coefficient
17.20	715658.99	19.00	2.00	17.00	3.00	0.93	19.00	17.00	0.00	0.56	0.00	0.00
17.20	715658.99	19.00	2.00	17.00	3.00	0.93	19.25	17.25	3.33	0.58	0.25	3.33
17.20	715658.99	19.00	2.00	17.00	3.00	0.93	20.00	18.00	3.55	0.50	1.00	3.55
17.20	715658.99	19.00	2.00	17.00	3.00	0.93	21.00	19.00	3.43	0.55	2.00	3.43
17.20	715658.99	19.00	2.00	17.00	3.00	0.93	22.00	20.00	3.54	0.51	3.00	3.54
17.20	715658.99	19.00	2.00	17.00	3.00	0.93	23.00	21.00	3.64	0.47	4.00	3.64
17.20	715658.99	19.00	2.00	17.00	3.00	0.93	24.00	22.00	3.69	0.45	5.00	3.69
17.20	715658.99	19.00	2.00	17.00	3.00	0.93	25.00	23.00	3.69	0.45	6.00	3.69
17.20	715658.99	19.00	2.00	17.00	3.00	0.93	32.00	30.00	3.46	0.55	13.00	3.46
17.20	715658.99	19.00	2.00	17.00	3.00	0.93	39.00	37.00	3.63	0.49	20.00	3.63
17.20	715658.99	19.00	2.00	17.00	3.00	0.93	49.00	47.00	3.68	0.48	30.00	3.68
17.20	715658.99	19.00	2.00	17.00	3.00	0.93	79.00	77.00	3.65	0.51	60.00	3.65
17.20	715658.99	19.00	2.00	17.00	3.00	0.93	109.00	107.00	3.62	0.53	90.00	3.62
17.20	715658.99	19.00	2.00	17.00	3.00	0.93	139.00	137.00	3.62	0.54	120.00	3.62
17.20	715658.99	19.00	2.00	17.00	3.00	0.93	169.00	167.00	3.82	0.47	150.00	3.82
17.20	715658.99	19.00	2.00	17.00	3.00	0.93	199.00	197.00	3.81	0.48	180.00	3.81
17.20	715658.99	19.00	2.00	17.00	3.00	0.93	229.00	227.00	3.73	0.52	210.00	3.73
17.20	715658.99	19.00	2.00	17.00	3.00	0.93	259.00	257.00	3.77	0.51	240.00	3.77
17.20	715658.99	19.00	2.00	17.00	3.00	0.93	289.00	287.00	3.81	0.50	270.00	3.81
17.20	715658.99	19.00	2.00	17.00	3.00	0.93	319.00	317.00	3.66	0.56	300.00	3.66

Creep prediction of concrete by **B3 Model**																
f'c (psi)	c (lb/ft3)	w/c	a/c	t (days)	t'	t-t'	E_{28}	q1	q2	q3	q4	Z(t,t')	Qf (t')	r(t')	Q (t,t')	Co (t,t')
2580.00	43.19	0.45	3.00	19.00	19.00	0.00	2895240.92	0.21	2.52	0.03	0.06	0.00	0.22	10.42	0.00	0.00
2580.00	43.19	0.45	3.00	19.25	19.00	0.25	2895240.92	0.21	2.52	0.03	0.06	0.14	0.22	10.42	0.14	2.68
2580.00	43.19	0.45	3.00	20.00	19.00	1.00	2895240.92	0.21	2.52	0.03	0.06	0.16	0.22	10.42	0.16	2.70
2580.00	43.19	0.45	3.00	21.00	19.00	2.00	2895240.92	0.21	2.52	0.03	0.06	0.17	0.22	10.42	0.17	2.71
2580.00	43.19	0.45	3.00	22.00	19.00	3.00	2895240.92	0.21	2.52	0.03	0.06	0.17	0.22	10.42	0.17	2.72
2580.00	43.19	0.45	3.00	23.00	19.00	4.00	2895240.92	0.21	2.52	0.03	0.06	0.18	0.22	10.42	0.17	2.73
2580.00	43.19	0.45	3.00	24.00	19.00	5.00	2895240.92	0.21	2.52	0.03	0.06	0.18	0.22	10.42	0.18	2.73
2580.00	43.19	0.45	3.00	25.00	19.00	6.00	2895240.92	0.21	2.52	0.03	0.06	0.18	0.22	10.42	0.18	2.74
2580.00	43.19	0.45	3.00	32.00	19.00	13.00	2895240.92	0.21	2.52	0.03	0.06	0.19	0.22	10.42	0.19	2.77
2580.00	43.19	0.45	3.00	39.00	19.00	20.00	2895240.92	0.21	2.52	0.03	0.06	0.20	0.22	10.42	0.19	2.78
2580.00	43.19	0.45	3.00	49.00	19.00	30.00	2895240.92	0.21	2.52	0.03	0.06	0.20	0.22	10.42	0.19	2.80
2580.00	43.19	0.45	3.00	79.00	19.00	60.00	2895240.92	0.21	2.52	0.03	0.06	0.21	0.22	10.42	0.20	2.84
2580.00	43.19	0.45	3.00	109.00	19.00	90.00	2895240.92	0.21	2.52	0.03	0.06	0.22	0.22	10.42	0.20	2.86
2580.00	43.19	0.45	3.00	139.00	19.00	120.00	2895240.92	0.21	2.52	0.03	0.06	0.22	0.22	10.42	0.20	2.88
2580.00	43.19	0.45	3.00	169.00	19.00	150.00	2895240.92	0.21	2.52	0.03	0.06	0.22	0.22	10.42	0.20	2.90
2580.00	43.19	0.45	3.00	199.00	19.00	180.00	2895240.92	0.21	2.52	0.03	0.06	0.23	0.22	10.42	0.21	2.91
2580.00	43.19	0.45	3.00	229.00	19.00	210.00	2895240.92	0.21	2.52	0.03	0.06	0.23	0.22	10.42	0.21	2.92
2580.00	43.19	0.45	3.00	259.00	19.00	240.00	2895240.92	0.21	2.52	0.03	0.06	0.23	0.22	10.42	0.21	2.93
2580.00	43.19	0.45	3.00	289.00	19.00	270.00	2895240.92	0.21	2.52	0.03	0.06	0.23	0.22	10.42	0.21	2.93
2580.00	43.19	0.45	3.00	319.00	19.00	300.00	2895240.92	0.21	2.52	0.03	0.06	0.23	0.22	10.42	0.21	2.94