Mechanics of Materials

a) Studies on Fiber Reinforced Concrete

Experimental and analytical investigation on load deformational response of partially prestressed concrete flanged T-girders (more practical representations) having fibers has been undertaken. The range of parameters considered in the experimental program were concrete strength, shear span to beam depth ratio, amount of conventional shear reinforcement (stirrup) deployed and fiber dosage and zone of fiber placement. Summary and findings emerging from these studies are:

- Basic mechanical properties of the composite material are at variance with the predictions based on the law of mixtures. Introduction of fibers in concrete results in a significant enhancement in energy absorption capacity but the improvement in ductility is limited to the stage prior to the initiation of yielding in the longitudinal rebars. Further, introduction of fibers in concrete results in a reduction in crack width and spacing (Figure 12).
- Introduction of fibers is found to be an effective substitute for stirrups in prestressed concrete sections and results in a shift in the dominant response from brittle shear to ductile flexure, even when fibers are introduced in limited regions of the beam. This has a practical importance in structural concrete sections that are heavily reinforced, where difficulties in constructability can be overcome through a careful introduction of fibers in the concrete matrix in some zones as a substitute for stirrups. Plain and fiber reinforced concrete exhibit considerable size effect, while in conventional reinforced concrete size effects are not as pronounced in comparison.
- An ANSYS based finite element model implementation to simulate steel fiber effects accounts and nonlinear phenomenon (bond-slip of longitudinal reinforcements, post-cracking tensile stiffness of the concrete, stress transfer across the cracked blocks of the concrete and load sustenance through the bridging of steel fibers at crack interface with progressive fiber pullout) has been undertaken. A Modified Compression Field Theory (MCFT) based nonlinear analysis has also been carried out to simulate the response of the partially prestressed beams containing fibers.

Studies on fiber reinforced concrete suggest that fiber dosages in structural concrete sections need to be carefully evolved and the yielding of primary reinforcement should be avoided in fiber reinforced concrete regions as the softening response at fiber pullout dominates the overall structural behavior.

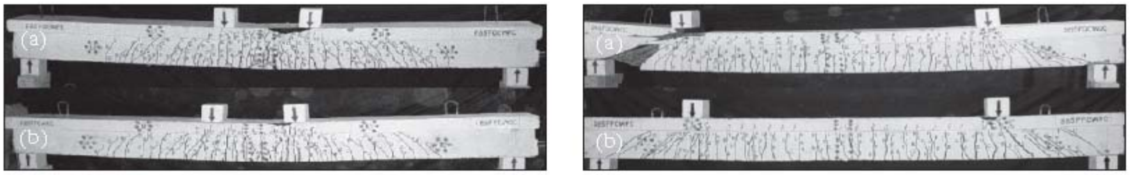


Figure 12: Typical crack patterns in flexure and shear RC beams with fibers in different regions

b) Studies on Creep and Shrinkage in Normal and Heavy Density Concrete

Estimation of creep and shrinkage are critical in order to compute loss of prestress with time in order to compute leak tightness and assess safety margins available in containment structures of nuclear power plants. Short-term creep and shrinkage experiments have been conducted using in-house test facilities developed specifically for the present research program on 35MPa and 45MPa normal concrete and 25MPa heavy density concrete. Drying shrinkage and creep in concrete have been quantified for different strength grades of normal and heavy density concrete under controlled relative humidity, temperature and age of loading. Summary and findings emerging from the study are:

- Existing empirical models for creep and shrinkage prediction have been used to simulate the test results and found to make satisfactory predictions for short term data, in particular for heavy density concrete. Limited number of short term measurements of concrete creep and shrinkage, along with water loss estimates in shrinkage specimen has been used to effectively predict longer duration measurements of creep and shrinkage for both normal and heavy density concrete (Figure 13). Extrapolation of the these models for very long term predictions of creep and shrinkage using Bayesian updating methods along with statistical sampling to account for parameter uncertainties has also been carried out.
- Scanning electron microscopy (SEM) images have shown differences in the extent of hydration in normal and heavy density concrete over the same period of time when cured under identical conditions. Higher levels of shrinkage and creep are present in heavy density concrete.

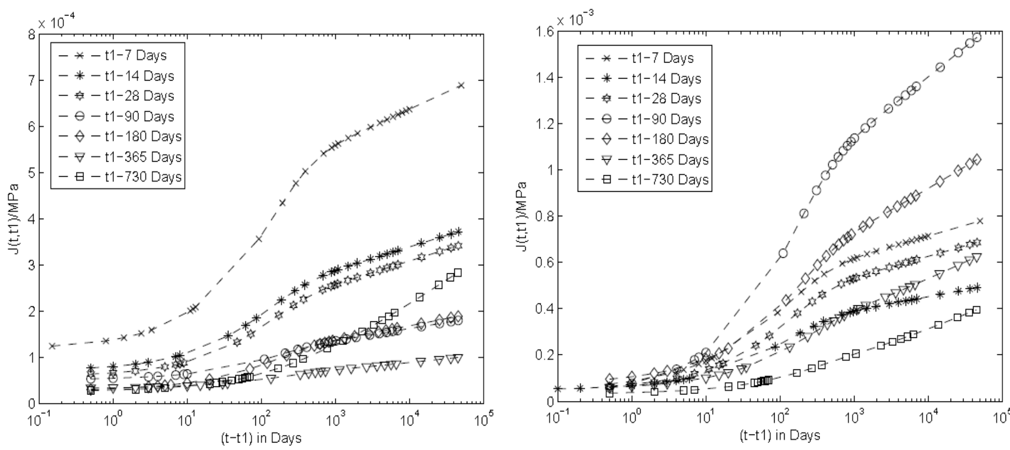


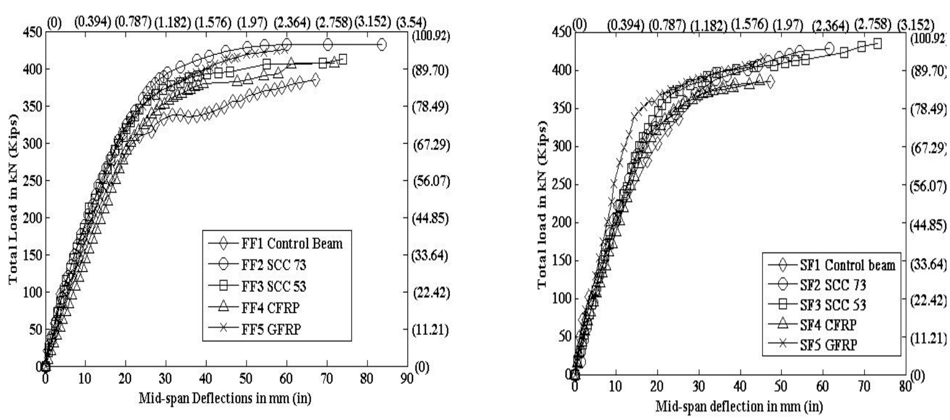
Figure 13: Long term creep prediction using short term data for normal and heavy density concrete

An analytical model accounting for the hygro-thermo-chemo-mechanical coupling (load levels, temperature, relative humidity, chemical composition and hydration rate) for creep and shrinkage prediction is under development. Nano- and micro-indenting of concrete samples used in creep studies is being undertaken to develop an understanding of the changes in the compliance of the hydrated concrete at different length scales across grain boundaries. Ongoing work on hygro-thermo-chemo-mechanical modeling of concrete to study creep and shrinkage will be extended to account for high temperature conditions, such as due to fires.

c) Studies on Repair of Concrete Elements

The condition of infrastructure, the constant need to repair and maintain them and the increasing costs associated with the maintenance has led to the search for replacements for steel in the concrete infrastructure around the world. Alternatives for repair and strengthening of concrete structures range from the use of glass (G) and carbon (C) FRP rebars replacing steel rebars to the use of FRP plates, fabrics wraps or the use of ultra high performance concrete (UHPC) elements as repair/retrofit to achieve required strength and serviceability requirements in structural concrete. Studies found that in comparison to FRP wraps, cement based repair has been found to offer enhanced ductility in the restored section through the mobilization of the tensile reinforcement in the primary structure and the concrete in compression, besides having the advantage of effective bonding with the primary concrete (Figure 14). Moreover, inaccessible regions can be repaired through effective concrete flow properties.

The use of chemical admixtures improves workability and the use of industrial wastes (fly ash or silica fume, etc) influences both mechanical and durability properties of concrete. The short term and long term consequences of these additives and admixtures in structural concrete need careful investigation both at micro and macro scale in a mechanistic framework. The repair materials range from carbon or glass fiber reinforced polymers based wraps or plates, fiber yarn based cementetious textile reinforced concrete to ultra high performance fiber reinforced concretes. Modern experimental techniques such as scanning electron microscopy and nano & micro-indenting will be employed to establish mechanical properties of concrete at different length scales and develop a multi-physics multi-scale numerical model to predict behavior of repaired/strengthened structural concrete under various loads.



(a) **(b)**

Figure 14: Load versus deflection of (a) flexure repaired and (b) shear repaired beams

d) Feasibility Studies on Use of GFRP Rebars as Reinforcement in Concrete

The primary objective of this investigation was to examine the suitability of pultruded GFRP bars as reinforcement in concrete structures. The problem of corrosion of ferrous steel rebars in concrete structures exposed to aggressive environments has been the main reason for looking at alternatives. In this investigation experimental studies have been conducted on flexure and shear critical beams reinforced with GFRP rebars having polyester and epoxy matrix. Feasibility of GFRP rings as stirrups has also been attempted. GFRP rebars have a smooth surface since they are pultruded, which affects its bond with the concrete. In this study its bond characteristics have been improved by (a) coating it with sand and (ii) by helically winding glass fiber roving around the bar and bonding it with epoxy. From our study sand coating the bar was found to be more effective in improving the bond characteristics of the rebar with the surrounding concrete. Since the failure in tension of GFRP bars is brittle in nature, the beam sections had to be designed as over reinforced section to prevent brittle failure of R.C. beams. Reinforced concrete beams reinforced with GFRP rebar exhibited higher deflections and crack widths compared to conventional ferrous steel reinforced beams. Summary and findings emerging from these studies are:

- GFRP rebar concrete interface behavior resulting in rebar slip/pullout controls the overall response and failure mode of the beams. A block type rotation failure was observed for GFRP reinforced beams, while flexural failure was observed in geometrically similar control beams reinforced with steel rebars. The relatively low elastic modulus of GFRP rebars, of the same order as concrete, resulted in large crack widths and deflections.
- Hybrid rebars consisting of a GFRP sheathing and steel core used to overcome the problem of steel corrosion and also augment the stiffness of the FRP rebar show some promise.

e) Behaviour of Stabilized Mud Block and Burnt Clay Brick Masonry and Stabilized Rammed Earth Walls

Large numbers of soil-cement block masonry buildings exist in India and in many other countries. Influence of soil grading on the characteristics of soil-cement blocks and shear bond strength of soil-cement block masonry was studied in detail. Influence of clay content of the soil-cement block on strength, absorption and durability characteristics, and interfacial mortar-block bond strength has been examined. Some of the major conclusions of the study are: (1) Optimum clay content leading to maximum strength is in the range of 14 to 16%, (2) Saturated water content of the blocks increases with increase in clay content of the block, (3) Initial rate of absorption (IRA) decreases with increase in clay content of the block, (4) Weight loss after ASTM wire scratch test is minimum when the clay content of the block is about 16% and (5) Optimum clay content for the highest modulus for the blocks and for highest shear bond strength is about 16%.

Cement soil mortar is commonly used for load bearing soil-cement block masonry. Properties such as compressive strength, bond strength, stress-strain relationships and elastic properties of soil-cement block masonry using cement-soil mortars were studied. Some of the major findings are: (a) initial moisture content of the block at the time of construction affects bond strength and use of partially saturated blocks is better than dry or fully saturated blocks (b) as the cement content of the block increases, its strength increases, surface pore size decreases leading to higher bond strength irrespective of the type of mortar (c) cement-soil mortar gives 15 – 50% more bond strength when compared to cement mortar and cement-lime mortar, (e) bond strength of cement-soil mortar decreases with increase in clay content of the mortar, (f) Masonry with cement-soil mortars shows higher modulus than the masonry using conventional mortars like cement-sand-mortar and cement-lime mortar. These studies clearly demonstrate the superiority of cement-soil mortar over other conventional mortars like cement-sand- mortar.

Influence of bed joint thickness and elastic properties of the soil-cement blocks, and the mortar on the strength and behaviour of soil-cement block masonry was investigated. The nature of stresses developed and their distribution, in the block and the mortar of the soil-cement block masonry prism under compression, has been analyzed by an elastic analysis using finite element method (FEM). Influence of various parameters like joint thickness, ratio of block to mortar modulus, and Poisson's ratio of the block and the mortar are considered in FE analysis. Some of the major conclusions of these studies are: (1) Masonry compressive strength is sensitive to the ratio of moduli of block to that of the mortar (E_b/E_m) and masonry compressive strength decreases as the mortar joint thickness is increased for the case where the ratio of block to mortar modulus is more than 1, (2) The lateral tensile stresses developed in the masonry unit are sensitive to the E_b/E_m ratio and Poisson's ratio of mortar and the masonry unit, (3) Lateral stresses developed in the masonry unit are more sensitive to the Poisson's ratio of the mortar than the Poisson's ratio of the masonry unit.

A BIS code entitled "Code of practice for manufacture and use of stabilized mud blocks for masonry" has been prepared and communicated to Bureau of Indian Standards for further processing.

Burnt clay bricks are used for load bearing masonry in India. There is a wide variation in the characteristics of bricks across the country. Properties of burnt clay bricks produced in different geographical regions of India were characterized. Properties such as strength, absorption and strain-strain characteristics were examined. The results clearly show that the common burnt clay bricks produced in the peninsular regions have very low modulus (400 – 1000MPa) when compared the burnt clay bricks available in Indo-Gangetic regions. These results are very useful in the design of masonry structures especially in selecting brick-mortar combinations leading to stiff brick-soft mortar combinations.

The strength and stress-strain relationships of brick masonry under compression have been evaluated for a range of different combinations of brick and mortar, representing soft brick – stiff mortar and stiff brick – soft mortar combinations. The results have also been generated for masonry strength using prisms, wallettes and full scale walls through extensive experimental programmes. Information on size effect and failure mechanisms of masonry under compression have been generated (Figure 15). Empirical relationships for masonry compressive strength as a function of brick and mortar strength in the Indian context have been derived.

Some issues pertaining to brick-mortar bond and masonry compressive strength have been examined. Failure theories for masonry under compression make an assumption that the bond between brick and mortar remains intact at the time of failure. Influence of bond strength on masonry compressive strength is not fully accounted for in these failure theories. Influence of bond strength on masonry compressive strength has been examined for the cases of E_b/E_m ratio <1 and >1 using burnt clay bricks as well as soil-cement blocks as masonry units. Masonry prism compressive strength has been determined when brick-mortar bond strength is varied over a wide range without altering the strength and deformation characteristics of bricks and mortar. Relationships between masonry prism compressive strength and bond strength have been obtained. The results clearly indicate that increase in bond strength, while keeping the mortar strength constant, leads to an increase in the compressive strength of masonry when E_b/E_m <1 and in the reverse case the masonry compressive strength is not sensitive to bond strength variations. This is a significant contribution to the knowledge on masonry behaviour under compression.

A 3D FE model for predicting the masonry compressive strength has been developed using a micro-modeling approach representing joints as continuum elements. Bricks and joints are modeled separately with individual properties, assuming a perfect nodal compatibility at the interface. Three dimensional non-linear analyses combined with a failure theory have been considered. Multi-linear stress-strain relationships have been used to model the non-linear stress-strain behaviour of each constituent of the masonry. Willam-Warnke five parameter failure theory developed for modeling the tri-axial behaviour of concrete has been adopted to model the failure of each constituent of the masonry. The post-failure regime has been modeled by applying orthotropic constitutive equations based on smeared crack approach. The model has been verified by comparing the experimental results generated for varying bed joint thickness.

The process of rammed earth wall construction, compaction energy implications, influence of clay fraction, density and moisture on rammed earth behaviour, stress-strain relationships, and elastic properties have been studied through an extensive experimental programme. Strength and stability of rammed earth walls through full scale wall tests has been studied. The results clearly indicate that (a) stabilized rammed earth possess two times more compressive strength than an equivalent masonry (b) Failure of rammed earth elements is characterized by shear failure (c) strength of stabilized rammed earth is sensitive to moisture content.

Hourglass type failure of bricks

Splitting, crushing of bricks and Diagonal shear failure of wall

Separation of the two leaves of the wall

Figure 15: Failure of storey height English bond burnt clay brick masonry wall under compression