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PERFORMANCE OF POLYMERIC CONCRETE WITH SYNTHETIC FIBER REINFORCEMENT AGAINST REFLECTIVE CRACKING IN RIGID PAVEMENT OVERLAY

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Abstract

Cement concrete pavements are used for heavy traffic loads throughout the world owing to its better and economical performance. Placing of a concrete overlay on the existing pavement is the most prevalent rehabilitating method for such pavements, however, the problem associated with the newly placed overlay is the occurrence of reflective cracking.

This paper presents an assessment of the performance of polymeric concrete with synthetic fiber reinforcement against reflective cracking in an overlay system. The performance of polymeric concrete with synthetic fibers as an overlay material is measured in terms of the load-deflection, strain-deflection and load-strain behavior of beams of the polymeric concrete. For this purpose, five types of beams having different number of fiber wires and position are tested for flexure strength. Deflection/strains for each increment of load are recorded. In addition, cubes of plain concrete and of concrete with synthetic fiber needles were tested after 7 and 28 days for compressive strengths. Finite element models in ANSYS software for the beams have also been developed. Beams with greater number of longitudinal fiber wires displayed relatively better performance against deflection whilst beams with synthetic fiber needles showed better performance against strains. Thus, polymeric concrete overlay with fiber reinforcement will serve relatively better against occurrence of reflective cracking.

Keywords: Polymeric, Concrete, Fiber, Reinforcement, Reflective, Cracking, Pavement.

1.0 Introduction

Construction of rigid pavements is essential for airports as well as for highways where weak subgrade exists or heavy traffic volume is encountered. Concrete is the most common material used in the construction of rigid pavements and overlays but the problem associated with concrete is its sensitiveness to moisture loss and shrinks whenever moisture loss occurs due to hydration of cement, evaporation, etc. If concrete member is restrained, then tensile stresses are developed in the concrete and when these stresses touch the tensile strength, cracks are formed. In case of an overlay over the existing pavement, the overlay is not free to shrink but is restrained by the existing pavement. Consequently, restrained shrinkage of the overlay will occur when it hardens and tensile stresses will develop in the overlay which will cause cracking when these stresses exceed the tensile strength of the overlay materials. The flexural stresses developed due to traffic loading and thermal stresses due to temperature changes also cause cracking of the concrete. Thermal variations within the pavement play an important role in the occurrence of reflection cracking. According to the classical fatigue theory, cracks due to traffic loads are initiated at the bottom of the bound layers and propagate upwards to the surface (Molenaar and Potter, 1997). Jeffery et al. (2005) studied the causes of reflection cracks in continuously reinforced concrete pavements (CRCP) and found the longitudinal steel as the major cause of the cracks in the concrete. Reflective cracking may occur due to horizontal and differential vertical movements between the existing pavement and the newly placed overlay (Harold et al., 2010). The phenomena of reflective cracking, associated with asphalt resurfacing, is the propagation of already

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occurred cracks in the old pavement into the new overlay (Farshad, 2005).

Due to increasing traffic volume on existing airports and roadways, major challenges are faced by road agencies because they have to repair deteriorated pavements to maintain smooth traffic flow on these pavements. To reduce reflecting cracking, several techniques including a seal coat application to the existing pavement, saw and seal the hot-mix-asphalt (HMA) overlay, cracking and seating of concrete pavements, use of geosynthetics, etc. are used.

2.0 Suggested Solutions in Literature to the Problem

Reflective cracking is one of the most significant factors in pavement deterioration and shortening of the pavement service life. The problem of reflective cracking is not new to the professionals of concrete industry. A lot of research has been done to find answer to this problem. Several techniques have been tried and are reported as partially or fully successful. Some of the researchers' work is hereby presented:

Hydraulic cement concrete overlays are used as a rehabilitation technique for both existing concrete and asphaltic pavements. The overlays may be bonded, partially bonded or not bonded (ACI Committee 325, 2006). Concrete pavements are popular for roads subjected to heavy traffic loads, such as highway networks and airfields, due to their high load carrying capacity and low maintenance requirement compared to flexible asphalt concrete pavements. Several hundred thousand kilometers of Portland cement concrete pavements have been built in US and in other countries in the past decades (Emmanuel et al., 1998). Zhang (2002) suggests asphaltic concrete and Portland cement concrete overlays as a rehabilitating method for pavements subjected to moderate and heavy traffics.

The first CRCP was constructed in 1921 on Columbia Pike near Washington, DC, for experimental purposes. By the start of 1940s and 1950s, many states within USA began conducting extensive studies on the effects of various designs and construction factors on its performance (Huang, 2004). Federal Highway Administration constructed different pavements sections consisting of bare PCC, AC overlay of non-fractured PCC, and AC overlay of fractured PCC. The agency observed that none of these sections exhibited reflection cracking during the first year following rehabilitation. However, most of the reflection cracking appeared during the second year after rehabilitation. However, relatively small increase in the length of the reflection cracking over time for all of the rehabilitation techniques was noted. In addition, the amount of reflection cracking does not significantly increase after this period. However, it is expected that these cracks will continue to deteriorate (FHA, 2006).

Most of the research to date on fibrous concrete has involved either steel fibers for structural enhancement or synthetic fibers for improved pavement performance by decreasing permeability and giving the concrete residual strength after the cracks occur. The steel fibers give the concrete increased strength and the synthetic fibers give the concrete increased durability and toughness (ACPA, 2006). Glass grid is a self-adhesive, low extension, stress absorbent asphalt reinforced membrane which combats the underlying tension forces that result in reflective cracking. Glass grid distinctly reduces surface cracking for normal life of the overlay until pavement fails through old age or loss of skid resistance. Glass grid controls cracking from lean concrete and other cracked sub-bases. It offers a solution to reflective cracking from cracks and joints throughout the pavement. It is used between bituminous layers on lean mix concrete, distressed concrete or roads founded on peat and clay (Road Surfacing, 2000).

Zhang (2002) presents an experimental study and theoretical analyses on the monotonic and fatigue performance in bending of a polyvinyl alcohol (PVA) fiber-reinforced engineered cementitious composite (ECC) overlay system. His experimental results showed that when ECC is used as overlay material, both load carrying capacity and deformability represented by deflection at peak load of the overlaid beams in flexure are significantly increased compared to those of plain concrete (PC) overlaid beams. The present study demonstrates that reflective cracking failure in pavement overlays can be eliminated by the use of a ductile material such as ECC.

The use of geo-synthetic stress relief interlayer on the pavement surface is found to delay occurrence of reflective cracking as this layer absorbs the stress and strain of the cracks that arise from the existing pavement. When reinforced, the geo-synthetic interlayer substantially enhances the tensile strength of the pavement (Rahul, 2004). An interlayer stress absorbing composite (ISAC) originally developed at the University of Illinois has been installed at a number of airports over the past five years in an effort to control reflective crack development in asphalt overlays (Bozkurt and William, 2002). Stress-relieving interlayers, such as paving fabrics, have been used in an attempt to reduce or delay reflection cracking. Studies have shown that nonwoven geotextile interlayer systems, known as the paving fabric, in conjunction with asphalt overlays, typically 1.5 to 2.5*in* (38.1 to 63.5*mm*), may be used to absorb the stresses normally transferred from cracks in the old pavement into the overlay and reduce or prevent the reflective cracking (Amini, 2005).

Research done in Nottingham University has proved that Tensar grid controls reflective cracking. The tests showed that the ordinary asphalt reinforced sample exhibited cracking after 425,000 cycles but the Tensar grid reinforced sample had not shown any sign of reflection cracking after 1 million cycles (Tensar, 2005).

Blankenship et al. (2003) found that by using the HMA (Hot Mix Asphalt) as an overlay, the cracks start to appear after three years and Roberts et al. (1996) found that HMA overlays usually exhibit reflective cracking, formed due to movements of underlying concrete slab; thus, the pavement serviceability reduces at a rapid rate. Researching on the same area, Ceylan et al. (2005) found that Hot Mix Asphalt overlay is the most commonly used rehabilitation technique for such deteriorated PCC pavements. However, the performance of these HMA overlaid pavements is mired due to the occurrence of reflective cracking, resulting in significant reduction of pavement serviceability. Various fractured slab techniques, including rubblisation, crack and seat and break and seat are used to minimise reflective cracking by reducing the slab action.

The performances of overlays consisting of fabric inter-layers is checked in the field and generally found satisfactory (Farshad, 2005). Janet and Chris (1999) studied the influence of bond between the Aramid fibers and concrete and concluded that before cracking occurs, the strains in the concrete are small and fairly uniform over the length of the beam so the degree of bond has relatively little effect on the behavior of the beam. However, once cracking occurs in the concrete, the amount of bond can have a significant effect. If the failure is dominated by the formation of one central crack, then it can be presumed that the bond between the fiber and the concrete is not significant, *i.e.*, the bond is insignificant whilst transferring the stresses from fiber to concrete. However if the failure is dominated by the formation of many small cracks, then it can be stated that the bond is significant whilst transferring the stresses from fibers to concrete.

Finite element analysis was performed by Elseifi and Al-Qadi (2003) and they present the development of an overlay design procedure to predict the service life of rehabilitated flexible pavement structures against reflective cracking. A simple equation was derived based on three-dimensional (3D) finite element (FE) models and by utilising linear elastic fracture mechanics (LEFM) principles. Hocho et al. (1998) studied the performance of asphalt overlay over rigid pavements and established a reasonable structural FE design scheme in ABAQUS. For preventing premature failure of rehabilitated rigid pavement, it is necessary to determine the load carrying capacity of the prerehab pavement and the resistance of overlay material to underlying crack/joint movement. Chen et al. (2010) employed two quantitative methods viz. the rolling dynamic deflectometer (RDD) and overlay tester (OT) in rehabilitation studies involving reflective cracks. The RDD is able to continuously assess vertical differential movement at joints/cracks that represent the potential for reflective cracks on existing pavement. The OT has the ability to determine the resistance of the overlay material to underlying cracks/joint movement. These tools were checked for rehabilitation of five different projects and were found to be satisfactory techniques. Chen (2008) also recommended the use of both the tools (RDD and OT) for rehabilitation of concrete pavement with an asphalt concrete overlay to evaluate the potential for reflective cracking. Yin et al. (2007)

investigated the elastic fields which develop in an overlay bonded to a rigid substrate when the system is subjected to thermally induced stress. A two-dimensional solution of the displacement field was derived for periodic discontinuities distributed in a hot mix asphalt overlay bonded to a rigid pavement.

Ceylan et al. (2011) developed and successfully used the neural networks (NN) methodology to model the stress intensity factor (SIF) as cracks grew upward through a Hot Mix Asphalt (HMA) overlay as a result of both load and thermal effects with and without reinforcing interlayers. Nearly 100,000 runs of a finite-element program were conducted to calculate the SIFs at the tip of the reflection crack for a wide variety of crack lengths and pavement structures. The NN method was found as rapid technique for prediction of SIFs as the overall computer run time for a 20-year reflection cracking prediction of a typical overlay was significantly reduced. Elseifi and Al-Qadi (2005) used steel paving mesh as reinforcement for hot-mix asphalt in new flexible pavement system. They constructed two road sections with three different types of steel reinforcement. The effectiveness of steel reinforcement in enhancing flexible pavement performance and resisting fatigue cracking was evaluated by instrument response to vehicular loading and finite element modelling. No comparison between the performance and effectiveness of two types of steel reinforcement was investigated; however, the contribution of steel reinforcement to the structure is believed to be of significant importance after crack initiation. Chen et al. (2001) conducted falling-weight deflectometer and dynamic cone penetration tests on pavement layers and recommended some typical ranges of base moduli for different pavement layers which will be beneficial to minimise potential premature failure.

3.0 Experimental Program

To assess the performance of polymeric concrete with synthetic fiber reinforcement, a polymeric concrete mix with special additives like Styrene-butadine co-polymer latex (SBR) and pulverised fuel ash (PFA) is prepared. The detail of the mix proportions are given in Table 1.

A synthetic fiber of tensile strength 327.42M*Pa* and elastic modulus of 6G*Pa* is utilised with polymeric concrete mix to replace traditional reinforcement.

Table 1. Polymeric Concrete Mix Proportion

Material	Quantities in Kg for one m^3 of the mix	Quantities in Kg taken per batch Volume($0.03m^3$)
Cement (OPC)	489	14.67
PFA	109	3.27
Coarse Aggregate of 10 mm size	1053	31.59
Fine aggregate of 0.14 mm size	549	16.47
MTK	40	1.20
Admixture (SBR)	31	930 ml
Water	184	5.52
Fibers	@ 2 kg/m^3	@ 2 kg/m^3

3.1 Casting and Curing of Test Specimens

Beam specimens and cube specimens are casted for testing flexure strength (modulus of rupture) and compressive strength respectively.

3.1.1 Beam Specimen

A special mold having six chambers was used for casting beams of 360*mm* x 60*mm* x60*mm*. The beam specimens are prepared according to the ASTM, C-192 test procedure. Five groups of beams designated as A, B, C, D and E are casted with different amount and position of fibers. Beam-A is casted from plain mix with no fiber wires, beam-B casted with five fiber wires, beam-C with four fiber wires, D with three fiber wires and beam-E with fiber needles @ 2kg/m^3. Two beams are casted for each group. The synthetic fiber reinforcements are passed through the holes provided in the mold according to the different group combination as shown in Figure 1.1. The specimens are demolded after 24 hours and kept in water till the day of testing.

3.1.2 Cube Specimens

Cubes of standard size (6in^3) were prepared from both plain mix and mix with synthetic fibre needles. The molds were filled in three equal layers; each layer was compacted by 35 strokes of 1*in* square steel punner. After 24 hours, these were unmolded and kept in water till the day of testing.

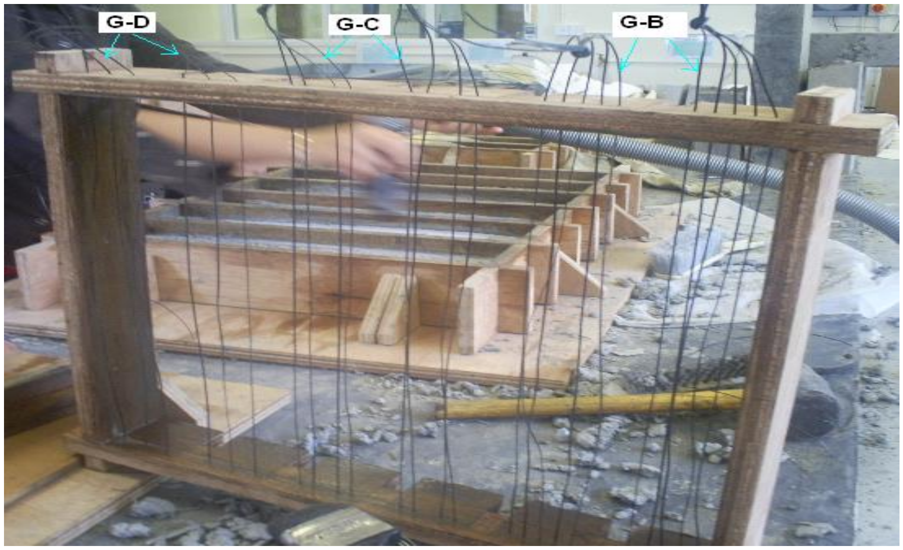

Fig. 1.1. Group wise synthetic fibers combination

3.2 Testing of Specimens

For testing of beams, the ASTM C78-75 (Flexure strength of concrete by testing simple beam with third point loading) was followed and modulus of rupture values for the beams of all the groups were calculated by the formulae recommended for the above test method. Deflection gauge was installed at the center line of the beam and mid-span deflections were measured for each increment of load.

Cubes were tested after 7 and 28 days, according to the BS 1881:1970 test method. Compressive strength was calculated by dividing the ultimate load by the area of the cube. An average value of three cubes was taken as the final value. A separate tensile test was also performed for synthetic fibres.

3.3. Computer Model

Finite element models were developed in ANSYS software for different group combinations of beams. The computer model was based on the Poisson's ratio and elastic moduli of synthetic fibre and polymeric concrete. Crude values taken from literature for them have been used in the computer model.

4.0 Results and Discussion

The flexure test results (modulus of rupture values) and compression test results are shown in the Tables 2 and 3, respectively. For comparison, load-deflection, load-strain and strain-deflection curves are plotted as shown in Figures 1.2, 1.3 and 1.4. Tensile test results for synthetic fibres are shown in Figure 1.6.

Table 2. Flexure test results (modulus of ruptures values)

Type of beam	Ultimate load (KN)	Modulus of rupture (PL/bd^2) in MPa
A	4.63	6.39
B	4.60	6.39
C	4.61	6.39
D	4.33	5.97
E	4.60	6.39

Table 3. Compressive strength test results.

Type of Mix	Density (KN/m^3)		Strength (N/m^2=MPa)	
	7-days	28-days	7-days	28-days
Plain polymeric concrete	2297	2295	66.30	73.59
Polymeric concrete with synthetic fibres	2298	2306	64.52	76.13

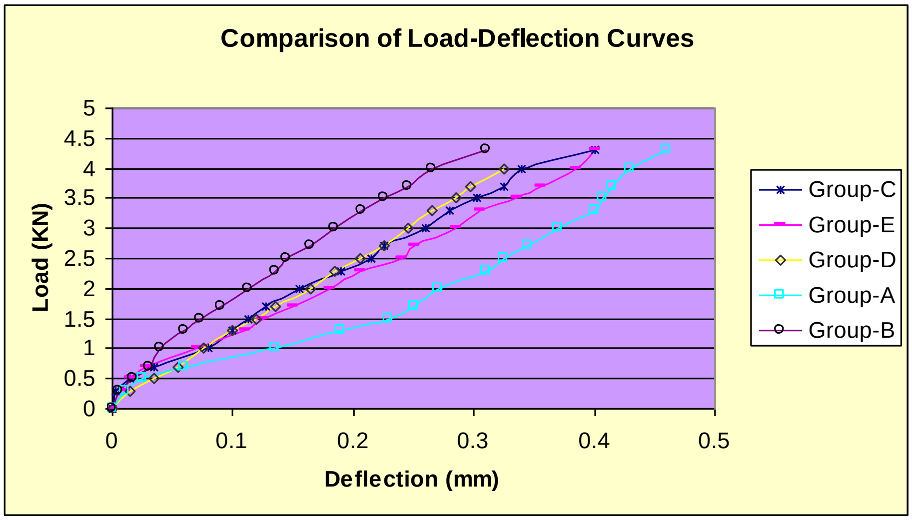

Fig. 1.2. Load-deflection curves for flexure.

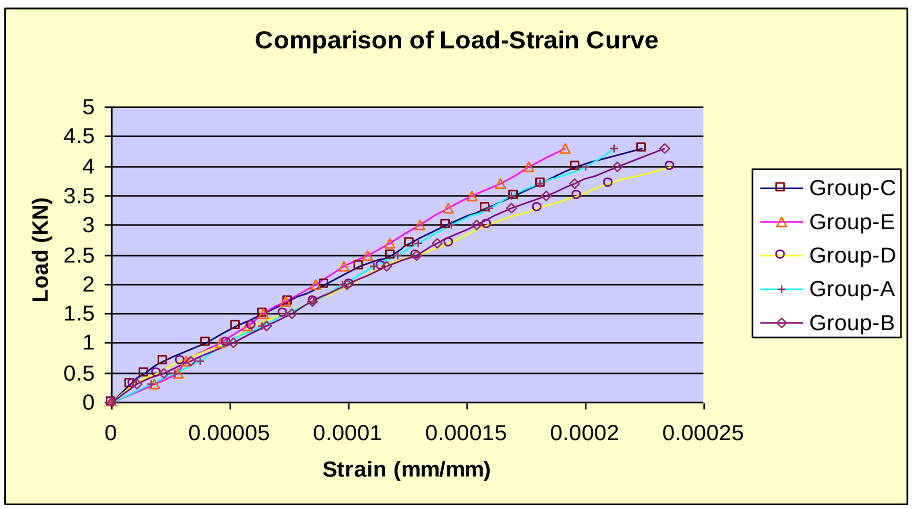

Fig. 1.3. Load-strain curve for flexure.

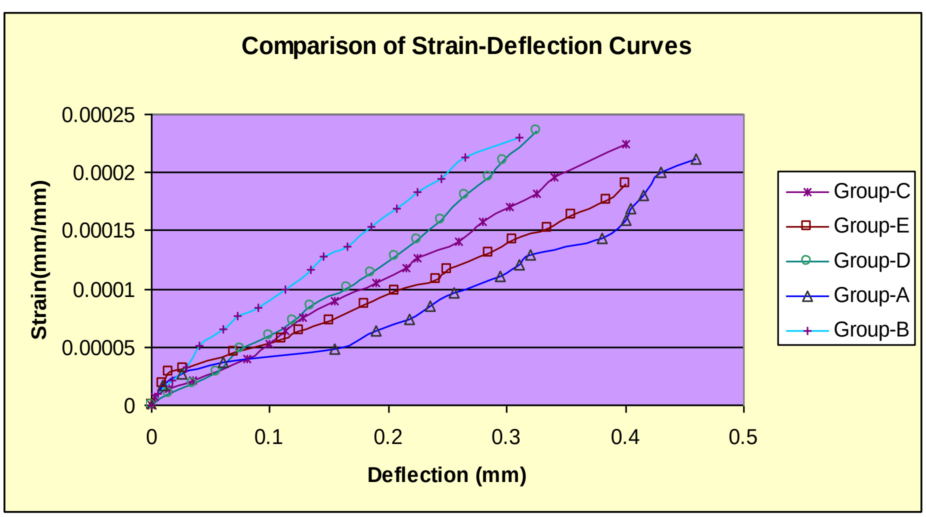

Fig. 1.4. Strain-deflection curves for flexure

The performance of synthetic fibre with polymeric concrete as an overlay material is measured by giving insight into load-deflection, strain-deflection and load- strain curves. The locations of crack formation are given exceptional considerations to evaluate the bond between concrete and synthetic fibre.

From load-deflection curve as shown in Figure 1.2, it is evident that beams of group-B (with maximum, five longitudinal synthetic fibres running across the length of the beam) have performed better against deflection as compared to other groups. The graph also shows that beams of group B demonstrate better bending capacity as compared to others. Group A is plain polymeric concrete without any fibres and these beams are less efficient to control deflection as compared to others.

By giving insight into load-strain curve as shown in Figure 1.3, it can be envisaged that beams of group-E (synthetic fibre needles added to concrete mix) have least strain values as compared to others. It is also obvious from the graph that synthetic fibres needles added to the concrete mix are efficient to control strains and hence the stresses. As there are no longitudinal synthetic fibres, its performance is less efficient as for as deflection is concerned.

Examining strain-deflection curve shown in Figure 1.4, comparatively high strains are produced in beams with greater number of longitudinal synthetic fibres, which is also confirmed by computer model. The performance of beams with longitudinal fibres, despite higher strain values, is better against deflection. Comparatively higher strains are produced at higher number of longitudinal synthetic fibres but they have better control over deflection. Also, at failure, it is observed that only one crack was seen despite multi-cracks in all beams as shown in Figure 1.5. This indicates that there may be a lack of bond between concrete and synthetic fibre or some weak portion may exist due to non-uniformity of the concrete. One reason of single crack formation is that some of the synthetic reinforcements were seen not properly embedded and hence it may have contributed to the formation of single crack.

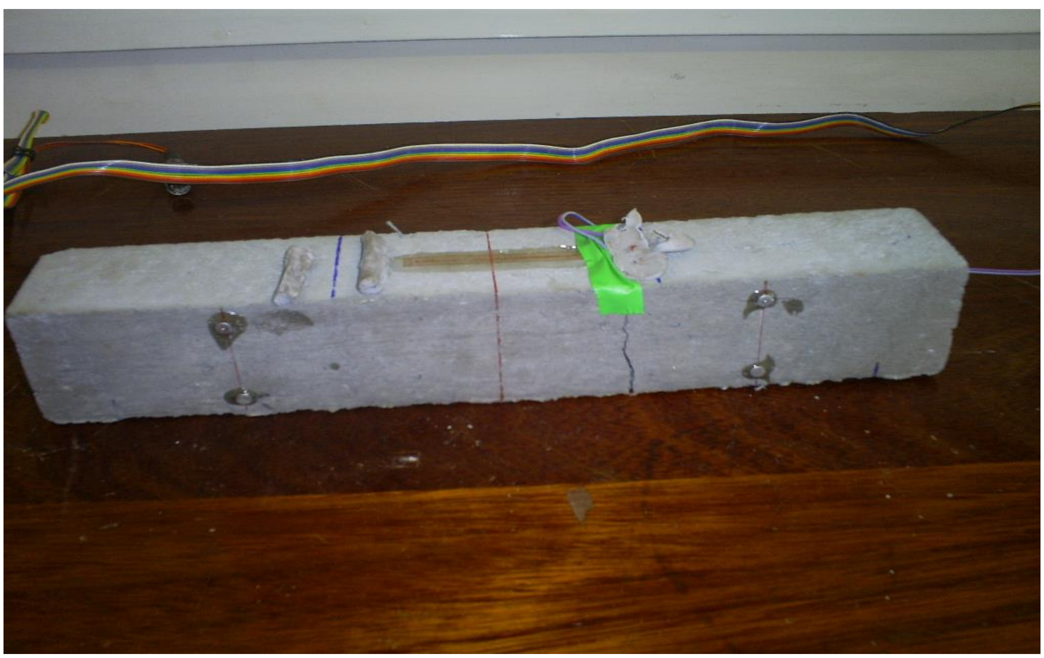

Figure 1.5. Beam at failure with one major crack

The modulus of rupture is calculated and the average value is considered for every group of beams. By comparing the modulus of rupture for different groups of beams, it is observed that all values are more or less the same. It is because the synthetic fibres were not properly embedded in the concrete and do not contribute towards flexural strength of the beams.

A brittle failure with no signs of warning is experienced in all beams. As compared to steel, the synthetic fibre is a less ductile material as is evident from the tensile test results for synthetic fibres given in Figure 1.6.

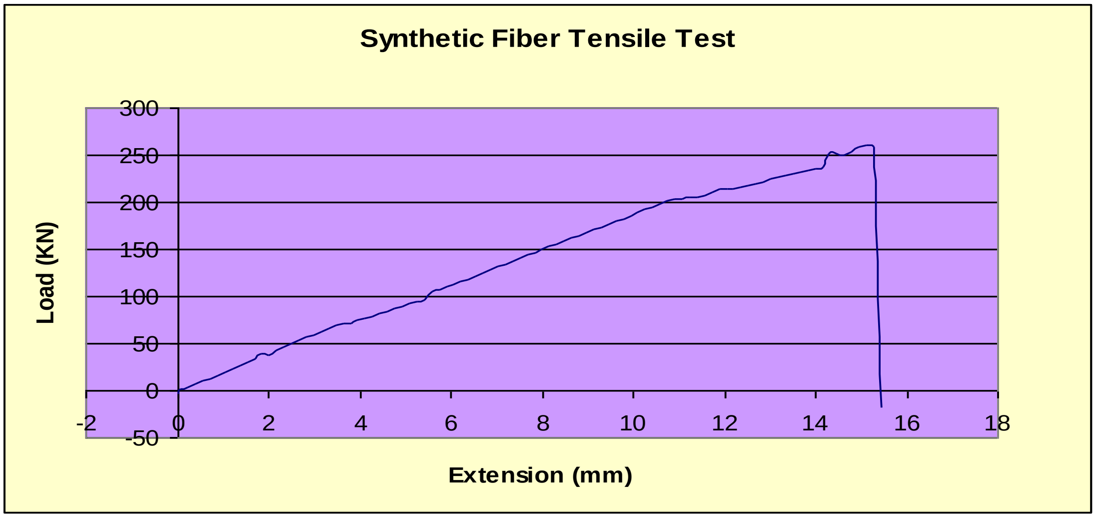

Figure 1.6 Load-extension curves for synthetic fibre

Unlike steel, synthetic fibre gives no warning before failure and contributes to the brittle failure of the beams as is evident from the graph above. However, apart from brittle behavior, the ultimate load carrying capacity of these fibres increases when there is a substantial bond between the concrete and fibres (Janet and Chris, 1999). Also, these fibres are less ductile than steel but energy dissipation via concrete cracking does ensure good ductility in fibre reinforced beams (Ana and Arup, 2004) whilst in CRCP, longitudinal steel is the major cause of the cracks in the concrete (Jeffery et al., 2005).

The above discussion indicates that an overlay with the cocktail of synthetic fibre needles in the concrete mix and the maximum number of allowable longitudinal synthetic reinforcement fibres will be able to control the strains and deflection. The synthetic fibre needles in the concrete mix will control the strain and the longitudinal synthetic fibres will control deflection. This amalgamation will be able to retard the reflective cracking if the bond between the fibre and concrete is achieved.

The laboratory test results have also been compared with computer model. The deflections calculated from computer have been observed to be very small as compared to the laboratory results. The strain and deflection based on the computer simulations are shown in Figure 1.7. From the graph, it can be seen that there is very little difference between the deflections among different groups of beams.

The graph also shows that the performance of beams reinforced with synthetic fibres is better against deflection than plain polymeric concrete. The values are very close together because the computer model can not detect the appearance of crack.

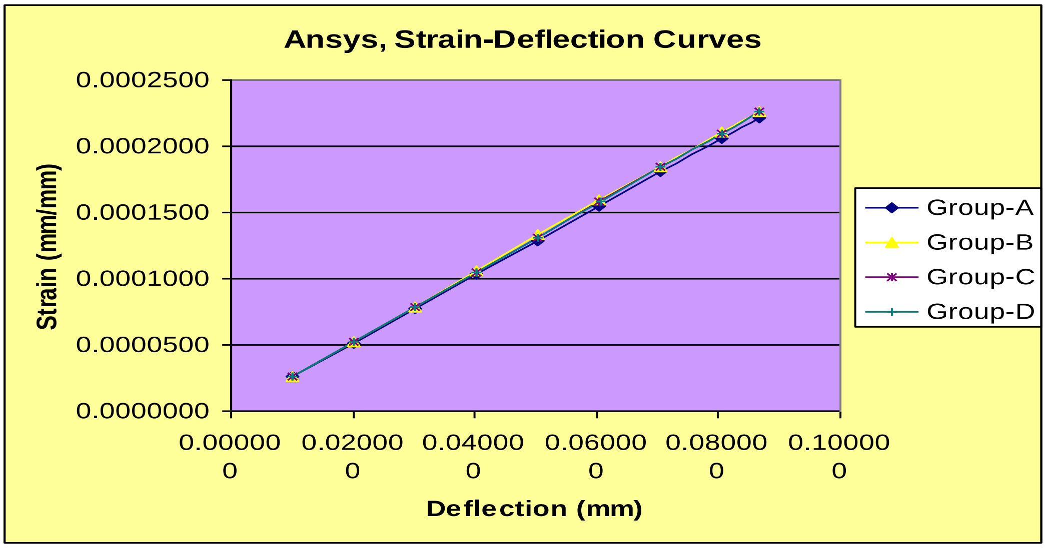

Fig. 1.7 ANSYS strain deflection curves

5.0 Conclusions

The following conclusions are drawn from the results of experimental tests carried out on fibre reinforced polymeric concrete beams followed by computer simulations:

1. Beams with the greater number of longitudinal synthetic fibres performed better against deflection as compared to the beams of other groups.
2. Beams with synthetic fibre needles performed better against strain as compared to the beams of other groups.
3. The appearance of one crack at failure indicates that there is lack of bond between concrete and synthetic fibre which encourages strain softening as compared to steel reinforced beams, where the formation of multi-cracks demonstrates that the bond between the concrete and fibres is good enough and the fibres are effective in stress transformation and strain hardening occurs. If the bond prevails between them, the above mentioned cocktail can be a compatible overlay to use to retard reflective cracking.
4. Laboratory tests indicate that a cocktail of synthetic fibres needles in the concrete mix and longitudinal synthetic fibres at the bottom of the beam will be able to control strains and deflections and hence be resistive against reflective cracking.
5. Future research is needed to upgrade the computer model and introduce ways to model the crack.
6. Testing of the fibre strand/needle cocktail in the field or laboratory.
7. Also, the bond between the concrete and synthetic fibre needs to be scrutinised.

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