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EVALUATION OF STRUCTURAL BEHAVIOUR OF POLYPROPYLENE FIBRE REINFORCED CONCRETE BEAM UNDER CYCLIC LOADING

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ABSTRACT

This research project is on utilization of synthetic fibres as intrinsic reinforcement in reinforced concrete beam in order to evaluate the structural behaviour of such element under cyclic loadings. The invaluable goal of this project is to improve the ductility and damping of the concrete beam element. The former helps eliminate or reduce the need for steel reinforcement in concrete structures and the latter provides characteristics with which the structure itself can be responsible for the dynamic loads, therefore the extra costs for external dampers can be eliminated.

A simply supported beam approximated as a single degree of freedom system (SDOF) is tested and analysed as part of this project. In such systems there is only one direction of movement defined for a mass under dynamic loads. Hysteresis loops are gathered by applying cyclic loads the results of which are analysed to evaluate the performance of fibre matrix in reinforced beam comparing to the conventional concrete. Results show that by adding Polypropylene fibres by specific percentages, it is possible to improve not only the mechanical performance of reinforce beam but also the behavior of the structural beam under dynamic loads. The behaviour of such beams demonstrated elevated performance to a considerable extend when PP fibres are included in the mix design.

KEYWORDS

Polypropylene fibre, fibre reinforced concrete, cyclic loading, damping.

INTRODUCTION

Response of a concrete structure to the loads applied is the main focus while analysing and designing structures. As the load is applied, structural elements are subjected to a series of compression and tension forces and stresses. As a matter of fact, the compressive strength of the concrete is incomparably higher than that of its tensile strength. Because of this deficiency, steel bars are used to reinforce the concrete structure in tensile zones. Another problematic issue regarding concrete structures is the energy dissipation or the damping properties of this widely used material.

This project studies the properties of non-traditional FRCs and researches dynamic mechanical performance of concrete mixes in structures. Findings of this research will determine whether FRCs,

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will provide improved mechanical performance under earthquake and strong wind load conditions. The findings of this research will be of significant to the construction industry in developing innovative, environmentally friendly and sustainable concrete mixes for improving the ductile and damping behaviour in structural applications. In places such as New Zealand or Australia, earthquakes or wind loads, respectively, pose high risks (such as partial failure of structural element, damage and collapse of the whole structure which can cause human casualties) to buildings and more specifically tall buildings. Vibration control to monitor and reduce resonance response of the structure, has been of great attention(Amick and Monteiro 2005). Two main sources of damping are categorised as intrinsic damping which is basically provided by the structure and the material, and the supplementary damping that is the additional devices attached to the structure such as tuned mass dampers, sloshing dampers, viscous dampers, and friction devices (Samali 5th Annual Wind Engineering Seminar). Damping ratios of plain concrete, with or without reinforcement, is known to have relatively non-desirable properties (Amick and Monteiro 2005). Accordingly, to improve the structural damping of buildings, additional dampers are introduced. The human resource, material and maintenance costs of these dampers are relatively high. Another issue is that these facilities are rather space consuming and therefore reduce the usable space during the life time of the structure. Concrete buildings are generally known to have damping of 1-3% of critical. If it is possible to increase this percentage up to 5% or more, dampers can be eliminated or reduced in some of the structures and save a lot of energy and money. It is also investigated that by increasing the damping ratio of the concrete to 10 or 15% the structure gains the capacity to dissipate the vibrating energy without needing any additional dampers(Ou 2002; Jinping, Tiejun et al. 2008).

In case of cyclic loading of a steel fibre reinforced beam, small compression strains were detected before the yielding point of the longitudinal reinforcement (Tavallali 2011). In the same research it is indicated that, a large residual tensile strain is observed after yielding of tension reinforcement. Damping, especially the structural damping is not easily measurable. Finding a suitable and appropriate model for the dynamic analysis of a structure is a complicated job. By utilising suitable methods to measure damping and dynamic characteristics of a structure, various characteristics can be identified. Usually structures have several elements which influence damping properties and make the process harder. For example, to evaluate the damping of a structure and energy dissipation within the system, material damping, and joint friction or radiation damping at the supports or foundation can be influential. In reinforced concrete structures, specifically calculating and measuring damping requires special attention as the material itself consists of two material, concrete and steel. However, it has been concluded that the hysteretic damping can be almost independent of longitudinal and confining steel bars(Fardis and Panagiotakos 1996). Using elastomeric polymers in the concrete mix can improve damping properties (Amick and Monteiro 2005).

A simply supported beam approximated as a single degree of freedom system (SDOF) is tested and analysed as part of this project. In such systems there is only one direction of movement defined for a mass under dynamic loads. Analysing a SDOF system gives a simplified way to evaluate the behaviour and characteristics of a more complicated system and get valuable information. A SDOF system behaves based on Newton's second law of motion involving mass and acceleration which is the second derivative of displacement. In dynamic loading, displacement of the structural system is very important and should be monitored and usually the attempt is to reduce these displacements and internal energy which causes a structure to collapse or be damaged. The effect of steel, glass and polypropylene fibre has been reported in an earlier investigation(Fanella and Naaman 1985) and have been reported to improve the post peak behaviour . With higher percentage of fibre content, the ductility and toughness and the energy absorption is increased moreover, the use of steel fibre in concrete can be very beneficial in improving the mechanical behaviour of the mix. Steel fibres have been investigated extensively during the past few decades. For instance, Craig (Craig 1987) studied that adding 2% by volume of the mix is very beneficial for the behaviour of the reinforced concrete beams. This study shows that by adding the mentioned amount of fibre into the mix design, increase in ductility, ultimate strength and especially the compressive strength and stiffness is observed. Soroushian and Bayasi (Soroushian and Bayasi 1991) investigated that using fibres in the mix can effectively improve the impact strength and toughness. Investigating the use of fibre in FRC, it is

reported that using fibre in concrete can enhance the bond between the steel reinforcement and concrete paste(Hota and Naaman 1997).

EXPERIMENTAL PROGRAM

Material and Methodology

Shrinkage limited Portland Cement (PC), with a typical fineness index from 310 to 370 m^2/kg is used in this project. Shrinkage limited PC is a special purpose PC manufactured from specifically prepared clinker and gypsum and often contains up to 5% by mass of mineral additions in accordance with Australian Standard (AS) 3972-2010 (StandardsAustralia 2010) Portland and blended cements specification requirements.

Since the goal of this project is to evaluate the dynamic behaviour and ductility of the structural concrete, the early low strength of the fly ash (FA) concrete is not going to interfere with the results. However, it is envisaged to create a concrete which is going to maintain its strength even in early days. The application of fly ash results in an ameliorated environmental friendly concrete which is also commercially beneficial. It is stated that the loss on ignition(LOI) for fly ashes used for cement additions must be usually less than 5%(Vandenberghe, de Resende et al. 2010). Also if an FA has loss of ignition above approximately 3% then the water required for the mix is higher(Feng and Krark 2001) due to the un burnt carbon portion of the FA. The FA selected for this study is a low-calcium type, with LOI lower than 3% as not to affect the water demand in mixes. The fineness by 45 μm sieve was found to be 94% passing.

In this project cement will be partially replaced with 30% FA. Fly ash, a by-product of coal combustion, has proved to increase the long term strength of concrete by prolonging the hydration process and improve the durability and flexural strength of the concrete(Malhotra 1990; Siddique 2004; Meyer 2009). FA is pozzolanic, which will react with calcium hydroxide and water to form a compound with cementing properties. The two products of cement hydration are calcium silicate hydrate (C–S–H) and calcium hydroxide (CH), and of the two products, C–S–H is the major contributor to strength. FA is an aluminosilicate, which reacts with CH to form additional C–S–H strengthening phases with increasing age by improving strength of the concrete in the long-term (Fraay, Bijen et al. 1989). With regards to other characteristics, it is reported that the Modulus of Elasticity of fly ash concrete is normally equal to or slightly better than that of a plain concrete(M.Neville July 1991). In this project the two most common types, monofilament and fibrillated PP fibres are incorporated. At hand technical data are detailed in Table 1.

Table 1. Properties of PP fibres used

Technical Data	18 mm Monofilament	19 mm Fibrillated
Nominal Diameter (μm)	22	55
Elongation at Break (%)	63	17
Melting point (℃)	160	160
Density (grams/ml)	0.91	0.91
Youngs Modulus (GPa)	3.5	3.5

Test Setup

There are 2 types of mix designs used for structural applications to cast reinforced beams. A control with 30% FA (CF), 0.25% of monofilament fibre (PM0.25%) and 1% fibrillated fibre (PF1%) has been used to test the beams under cyclic loading. Beams with the following specifications are used to measure the cyclic performance of the concrete. Beam1 as CF: 70% PC+30% FA; beam 2 as PM0.25%: CF+0.25% monofilament PP fibre; beam 3 as PF1%: CF+1% fibrillated PP fibre.

To make the beams, initially the steel bar cages were prepared and strain gauges were mounted on the bottom steel reinforcement at the *centre* point and third span. Thereafter, steel bars were placed into the moulds and concrete was poured. Beams were cured for 7 days and were de moulded after that and kept in a secure place to keep them from any accidental impact. A schematic of the reinforcement and beam dimensions are shown in Figure 1 and Table 2.

Table 2. Specimen details and test strength

Beam	Section			Longitudinal Reinforcement		
	Width-*b* (mm)	Depth-*D* (mm)	Strength-f'_c (MPa)	Bar diam. (mm)	Yield stress (MPa)	Number of bars
CF	150	200	57.5	12	500	3
PM 0.25%	150	200	66.5	12	500	3
PF 1%	150	200	58.0	12	500	3

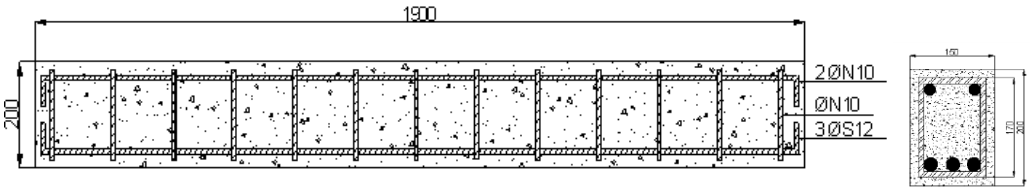

Figure 1. Reinforced beam test schematic

The test set up in this section of the project is a simply supported beam carrying a single concentrated point load at the centre. The maximum deflection happens in the centre of the beam and is given in equation (1):

$$\delta_{max} = \frac{1}{48}\frac{wL^3}{EI} \tag{1}$$

RESULTS AND DISCUSSIONS

Material Testing

Data from tests pertaining to the fresh properties of FRCs are presented in Table 3 showing the fresh properties of mixes containing PP fibres. The amount of cementitious material as well as aggregates, water, HWR, fibre are detailed before. The amount of High Range Water Reducer (HWR) used in each mix has been different as a slump of 80mm was targeted. Mass per unit volume of the concrete mixes has also been measured to have the volume density of the engineered concrete. Usually, the volume density of conventional concrete is approximately 2,400 to 2,500 kg/m3; this property is measured then to evaluate the effects of fibre on concrete density and also use this value for further calculations. Air content (AC) is also measured and presented. Knowing the amount of entrapped air in the concrete helps with quantitative analysis of the test results and may help explain certain behaviour of the concrete mix. Results of Table 3 show that, the amount of HWR used in monofilament containing mixes was much higher than that of fibrillated fibres which show that monofilament PP fibres decrease the workability of the mix more than fibrillated PP fibres. In mixes where fibres are present, a decrease in volume density is observed. This is most probably due to the lower volume density of PP fibres.

Table 3. Fresh Properties

Technical Data	W/C	Slump (mm)	HWR (ml/ m^3)	AC (%)	Volume Density (Kg/m^3)
CF	0.35	75	1000	1	2450
PM 0.25%	0.35	60	1923	1.8	2380
PF 1%	0.35	65	1846	1.5	2290

Results of compressive tests are illustrated in Table 4. Regarding the effect of PP fibres on hardened properties of concrete some conclusions are presented. Due to the presence of FA in the mixes, all compression tests were also performed to obtain 56 day compressive strength. Considering the compressive strength properties it is observed that in FRCs, 0.25% of monofilament PP fibre has reached the 56 days compressive strength in earlier age comparing to the control concrete. In lower percentages (0.25%), PP fibres have contributed to the compressive strength properties and have improved the compressive strength by nearly 3% in FRCs. PM0.25% has achieved the 56 day strength earlier and gained higher strength than normal concrete in 56 days. Most of FRCs strength is comparable to that of reference at later ages. With this particular fibre, the strength gain reaches the reference at 18 days and starts to improve with time. After 56 days, the compressive strength curve seems to get closer to the reference concrete and continues a parallel trend with the reference concrete.

Table 4. Compressive Strength

Technical Data	7-days	28-days	56-days
CF	46.0	57.5	70.3
PM 0.25%	38.0	66.4	72.1
PF 1%	38.5	58.0	65.6

3-Point Test, Cyclic Loading

From the tests conducted on the FRC beams, and related reference beams, the following results are derived. As mentioned before, a SDOF system which involves the viscous damping has been used. Therefore, the results are discussed using related formulations and theory. In each cycle of the harmonic loading or vibration, a certain amount of energy is dissipated which causes the changes in the damping and energy dissipation of the cycle after and also a bigger displacement amplitude.

Hysteresis diagram is derived from several loadings of the material not directly to failure but below the yield point and then unload. Doing so, the material bonds break and convert the strain energy to thermal energy. Generally, the hysteresis loop is plotted from the load displacement data and the area enclosed by the curve is the strain energy dissipated during the loading and unloading cycle. The damping ratio is related to the magnitude of the damping force which the system is undergone. It is worth mentioning that the free damped vibration of a SDOF system is cyclic but decays with time.

A description of how the damping and energy dissipation can be described from a book on dynamics of structures (Chopra 2011) is detailed below. The formulation shows how damping and energy loss is defined. The ratio of the strain energy E_{s0} to the energy loss in a cycle is called the specific damping capacity which is used to determine the energy loss and damping ratio. E_D is defined as the area under the curve in the negative part of the diagram. The energy loss is defined as ξ and calculated using the equation bellow:

$$\xi = \frac{1}{2\pi}\frac{E_D}{E_{S0}} \tag{2}$$

$$E_{S0} = \frac{ku_0^2}{2} \tag{3}$$

Where equation (2) and (3) is the strain energy calculated from the stiffness determined by the experiment if the load displacement loop is not available. In the case of this project, the full history curves are available to calculate E_{s0} and E_D. Using above parameters, damping is defined as:

$$\zeta_{eq} = \frac{1}{4\pi}\frac{E_D}{E_{S0}} \tag{4}$$

These concepts are used in this research work to calculate the energy loss and damping ratios in order to be able to evaluate the behaviour of the FRC in a reinforced concrete beam under cyclic loading. In the case of the reference concrete CF, as it shows a very brittle behaviour which after a few cycles the cracks propagated to an extend that loading it on the negative side (pull) would cause the beam to undergo premature failure. Therefore, for that specific mix design the beam was not loaded to higher

loads and the damping ratio of the full cycle is not even comparable to other mixes. For each mix the total damping ratio and the energy absorbed is demonstrated in Table 5.

Table 5. Damping ratio and energy absorption of beams

	CF	PM 0.25%	PF 1%
Total damping for all cycles	0.54%	0.67%	1.24%
Damping for the push loading	0.52%	0.56%	1.11%
Total energy dissipated in all cycles (J)	3,819	4,069	4,411
Energy dissipated in push loading (J)	3,780	3,945	4,279

Figure 2, shows the relationship between the damping ratios of different mixes comparing to their relevant reference mix.

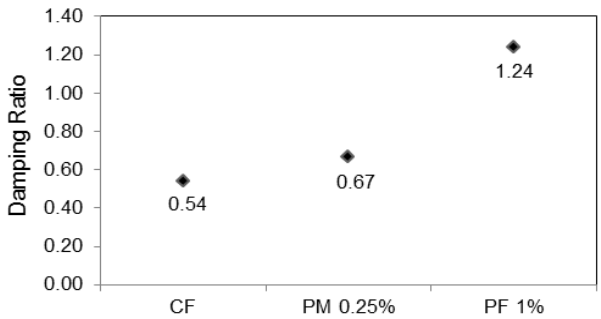

Figure 2. Comparative damping ratios.

It is observed that by adding elastomeric material to the mix by a considerable amount, it is possible to improve the structural elements behaviour under dynamic loading, to be able to prevent any severe damage in moderate loads and also prevent premature collapse of the elements. By using PP fibres in the mix, especially higher percentages, the structure will be dissipating a considerable amount of energy within itself and maintain a safe structure in case of dynamic loadings. By looking at the damping ratios and also the ductile behaviour of the beam, it can also be observed that adding PP fibres dramatically help with the improvement of the dynamic and mechanical properties of the concrete reinforced element. Figure 3, shows the maximum deflection of each beam and also the related max load in which the beam fails at the push section.

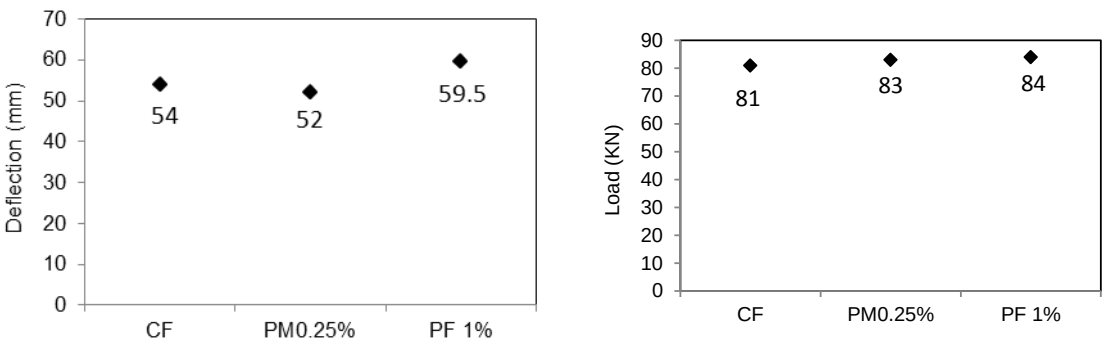

Figure 3. 3-point tests, max load and deflection.

Using 1% PP fibres increases the maximum deflection which is due to the bridging effect of the fibres in the mix. Generally the higher the fibre content the more effective the bridging effect can be and fibrillated fibres have proven to help with the mechanical characteristics of the mix while maintaining the fresh and rheological properties. In the case of the maximum load under 3 point cyclic test, as mentioned before, the damping ratio in the first cycle for the beams containing polymeric material is much higher than the conventional beam and also is higher than the other cycles. By comparing the energy dissipated in each cycle, this trend can be re-checked.

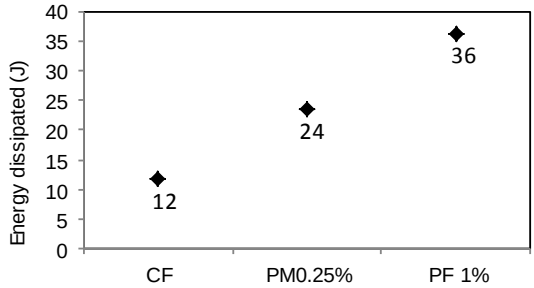

Figure 4. Energy dissipated within the first cycle

RESULTS AND DISCUSSIONS

In Figure 2, the bond strengths predicted using the proposed bond-slip models are compared with the results of the 253 pull tests in Lu et al.'s (2005) database. It can be seen that the proposed bond-slip models give results in close agreement with the test results and perform better than any other bond-slip models. The results of the precise model and the simplified model are almost the same, with the precise model performing very slightly better. Table 1 shows that the prediction of the proposed bi-linear model for the bond strength, which can be given as a closed-form expression (Lu et al. 2005), performs significantly better than all existing bond strength models except Chen and Teng's (2001) model. For the prediction of bond strength, Chen and Teng's (2001) model is still recommended for use in design due to its simple form and good accuracy.

CONCLUSIONS

Findings of this research project reveals that where fibres are used in the mix, damping ratio can be greatly enhanced. The natural frequency of undamaged beam drops to 90% comparing to reference concrete using 1% PP fibre in the mix . Using higher percentage of PP fibre in the mix, helps with the improvement of damping ratio and also the energy dissipated in the system. By adding elastomeric material i.e. PP fibres the damping regime changes (there is a large damping observed in the first cycle of the cyclic test). Furthermore, the energy dissipated in the first cycle of the beam containing 1% PP fibre is observed to be equivalent of the total energy dissipated in the first three cycles of the reference beam.

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