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THEORY AND PRACTICE ABOUT FIBERS, FIBER REINFORCED CONCRETE, AND APPLICATIONS

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Abstract

Fibres are discontinuous reinforcement that changes the performance of the entire system, including concrete material properties and structural response. There are many designs and choices to be made from the various types of fibres, concrete, and their respective constructions. Analysis and determining how well suited these materials and systems are for the project needs is the work and art meeting the customer's project needs. Typically, this effort includes logical connection and balance between theory and practice for calculations, sample testing, and construction. Simple techniques and methodical comparisons are discussed for choosing and evaluating fibre reinforced concrete. This includes discussion on significant differences in fibre material properties. The design and evaluation techniques include how to dis-assemble and then re-assemble the system behaviour. Limited projects and test results are presented to support the interpretation of the many differences in the details of these fibre reinforced concrete projects.

Keywords: fibre reinforced concrete, FRC theory and practice

1. Introduction

Dear authors, thank you very much for the submission of your paper to the 7th International Conference FIBRE CONCRETE 2013.

Concrete material properties are frequently confused with structural behaviour. A concrete cube or cylinder tested in compression is not a structural column. Testing in compression, the load increases until it drops. The peak load is considered failure and reported as the compression test value. The obvious difference between the test specimen and structural element is easy to understand. However, what may not be so easy to understand is that concrete does not fail in compression but in tension. A prismatic concrete specimen used in a flexural test is also neither a beam nor a column. A column can be described as a vertically positioned beam. Using Euler's formulas or the simple elastic beam theory equation can determine the load capacity of a flexural element. Stiffness is part of these engineering mechanics equations. Strength can be very easily confused with stiffness and concrete cracking. Increasing the concrete strength does not always reduce the probability of cracking. Changing the strength of the materials and the geometric shape are ways to

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change the stiffness and cracking probability of any structural element. Every concrete customer and project participant needs enough concrete strength and wants no cracks in the concrete. Obtaining the concrete strength is controlled, well documented, and mostly understood. However, obtaining no cracks is elusive and difficult to control. Many cracks in concrete can be due to not enough strength (material property) but that is significantly different than availability of enough design strength (structural requirement). Concrete also cracks because of excess deflection. However, concrete cracks for a myriad of reasons and not just because of not enough strength or excessive deflection from ACI 224R-01.

2. Paper Significance

Many fibre reinforced concrete papers are from a masters or doctoral thesis. The purpose of technical publishing should be an exchange of helpful information for the audience. Fibre reinforced concrete basic education is missing in most published paper discussions. The market needs basic education and project information about fibre reinforced concrete. Increasing fibre usage has passed the novelty stage and is capturing more of the reinforced concrete market. One way of learning is to draw comparisons to existing understanding by describing features, advantages, and benefits.

3. Discussion

A choice to use fibres can also be made on the basis of the scientific method of repeatable observation and not just on the basis of understanding the behaviour. Older teaching methods for reinforced concrete describe optimization as cycling between design – making a choice – and analysis – evaluating how good a choice was made. In practice then, why not change to fibres? Some objections to not using fibres are because previous choices not using fibres have been good enough, not using fibres is consistent with everyone else, and finally, not using fibres is consistent with training and education. However, some “design” with fibres needs to be ‘analysed’ for the change to fibres to be “optimized” because fibres have features, advantages, and benefits for projects.

The significant design decisions for a ‘slab’ are the concrete strength, concrete thickness, and the purpose for reinforcing the concrete. Reinforcing concrete is properly understood for tension or bending but many times used for other reasons in regular practice. For a slab analysis, the concrete thickness and strength are needed, and if reinforcing was used, then yield, size, location, and spacing are also needed. The reinforcing location in the cross-sectional depth is sometimes NOT needed for bending capacity. Tension is the more significant design controlling issue because slabs on ground are supported. Reinforcing materials hold broken concrete together and redistribute stresses before and after the concrete cracks. Concrete needs to break for the reinforcing materials to hold the concrete together. The capacity of the broken concrete in tension is determined by the strength of the reinforcing material times the area within a unit width of the slab. Further, both the tensile and bending strength capacity of the unbroken slab are usually greater than the strength capacity after the slab has broken using the reinforcement material across the crack. This difference in capacity is usually both a shock and conundrum to many involved in a slab behaviour discussion. Because unbroken concrete can be stronger than broken concrete with reinforcing, reinforcement can be analysed as unnecessary. Many others are confused because reinforcing does not keep the concrete from cracking. There are many other myths and misunderstandings about concrete, Wilson 2006.

Reinforced concrete design equations balance compression and tension forces. Steel is assumed in the tension zone, Wang 1973. Chapter 22 of the ACI 318 building code provides design methods for not reinforced or plain concrete and includes the flexural strength of concrete. This simple elastic beam equation also balances compression and tension forces. The un-cracked concrete is assumed elastic in the tension zone. The flexural strength of concrete is expressed as a constant times the square root of the compressive strength, ACI 318-08. For analysis purposes, higher values would be expected using test results for modulus of rupture. The value from this equation for flexural strength is a lower bound limit for flexural design purposes. Also, current design approaches use factored loads. There is no given design value for tensile strength. Tensile strength is sometimes assumed to be the same as the modulus of rupture tension test or three quarters of the rupture test. The real tensile value of concrete is further obfuscated by discussions regarding test specimen size effects and coarse aggregate size as discussed in Neville 1996.

Basic material properties of unreinforced and fibre reinforced concrete can easily be tested. The peak load during testing cracks the concrete. These loads are interpreted by engineering mechanics to give material property values for compressive and tensile-flexural. These material properties at cracking are essentially the same whether unreinforced or reinforced concrete with conventional reinforcing or fibres. There may be slight differences but these are statistically insignificant with most fibre dosages less than 1.0% by volume, ACI 544.1R-96. However, toughness testing is more difficult to understand. Toughness of post cracked unreinforced and reinforced concrete has significant differences. Conventional reinforced concrete and fibre reinforced concrete accomplish the same goal after cracking the concrete. The “reinforced” concrete is held together and carries measurable load. The unreinforced concrete cracks, there is nothing to hold the concrete together, and the system fails to carry load across the crack. Failure is better described as carrying no load across the crack rather than just cracked concrete. Failure needs to be agreed to in “real” projects.

Most concrete practitioners are trained in the strength of materials discipline, and within their projects, test to control strength. Further, most concrete practitioners ignore the potential for cracks and fatalistically accept “uncontrolled” cracking. Most design and analysis with testing provides values for at - cracking of the concrete or after - cracking. However, since reinforcing by definition also redistributes stresses before the concrete cracks, design is not done that way. Therefore, the methods of design and analysis of reinforcing are based on cracked concrete. Strength alone is not adequate to explain the many fibre reinforced concrete projects without cracks. Further, regarding slabs on ground, there are many fibre reinforced concrete projects with not activated saw cuts and significant distance between cracks, MacDonald 2005.

4. Basic Definitions and Further Background Explanations

Reinforcement for concrete is not steel by or in itself. Reinforcing or reinforcement materials are whatever holds broken concrete together and redistributes stresses before and after the concrete cracks. Fibres are different shapes, sizes, and lengths and made of primarily these four material groups: steel, synthetics, glass, and natural, ACI 544.5R-10. Fibres are discontinuous as opposed to continuous conventional reinforcing, so the mode of failure is usually not by yield of the materials but by pull out of the fibres at the matrix - fibre interface. If the load decreases with increasing strain after cracking, fibre reinforced concrete is considered strain softening; if the load goes up with increasing strain after cracking, the fibre reinforced concrete is considered strain hardening. Fibre reinforced concrete strain softening or hardening is dependent on fibre dosage. The typical elastic equations define FRC strengths both pre and post cracking. Toughness is defined as area under the stress - strain or load deflection curve. The strength - controlled test for toughness is ASTM C 1399-10. A deflection-controlled test for toughness is ASTM C1609-10. The significant difference in these tests is that deflection control never naturally occurs.

5. Testing Discussion

There is a normal variance in testing and this is why an average of 3 cylinders for compressive strength is typically used. However for FRC, the experience in trouble shooting variance in testing results is missing as discussed further by Patnaik 2007. ASTM committee C9.42 Fibre Reinforced Concrete and the Fibre Reinforced Concrete Association are very concerned with these variances because these variances can become the competitive advantage or disadvantage depending on the values higher or lower per fibre dosage as more or less economical and more or less efficient. The engineers and marketing departments of the fibre suppliers have "interesting discussions" regarding the truth of these matters. This difference in values does nothing for the fibre customer other than what all customers want - find someone to trust. Further, customers do not understand FRC for many reasons and look for any excuse not to buy any fibre product.

The ASTM committee has three toughness tests for FRC, one round determinate panel type test, deflection controlled, and two beam type tests, one deflection controlled and the other strength controlled. Correlation between these tests is not readily apparent but there definitely is toughness or load carrying of the FRC matrix after the concrete has cracked. The ASTM committee is working to reduce variance in testing, casting, and sampling FRC specimen. Simply put, FRC is not the same as plain concrete.

6. Behaviour of Post Peak and Cracked FRC

Prior to cracking, the FRC behaviour depends mostly on the behaviour of the concrete. This can easily be understood when the fibre dosage is less than 1% by volume within the concrete. A 1% difference in the material properties is not sensitive enough to the rule of mixtures. Post peak (cracked) FRC behaves according to three materials, fibres, concrete, and the environment across the crack. This post peak behaviour is also according to two interfaces, one between the fibre and concrete and the second between the fibre and the environment across the crack. The dimensional details and material properties of the three materials have considerable influence with the interfaces and behaviour of the entire FRC system.

Cracked FRC still behaves according to normally understood transformation of sections for material property substitutions for strength. Equal strength can be achieved with different material property strengths using good engineering judgment and simple mathematics. A significant advantage of synthetic macrofiber reinforced concrete is equal strength and no corrosion. Corrosion is an issue with ferrous materials and is allowed for with clear cover and other protective coatings and other methods to buy time, but the ferrous material eventually corrodes

7. Theories to Explain the Behaviour of FRC

Fibre reinforced concrete works and behaves the way it does according to two underlying theories: strength of materials and fracture mechanics, which are summarized in Table 1. Most concrete practitioners are trained in only one discipline, strength of materials. The two disciplines are different, and they are compared and summarized in Table 2. Many successful projects cannot be fully explained by one "correct" discipline concerning fibre reinforced material behaviour.

Tab.1: Behaviour theories FRC

	Strength of materials		Fracture mechanics
1	Reinforcement	1	Fracture Toughening
2	Bond and Anchorage	2	Energy Absorption
3	Strong Stiff Fibers	3	Fíbre count
4	Significant Damage	4	Significant Integrity
5	Fíbre force	5	Matrix force
6	Spans Over Cracks	6	Matter States and Ages

Tab.2: FRC theory differences

	Strength of materials		Fracture mechanics
1	Determinate	1	Indeterminate
2	Factors of Safety	2	Unknowns
3	Load Factors	3	Concentrators
4	Tables and Codes	4	Experience
5	Historical	5	Predictive
6	Strength	6	Stress

Strength of materials is determinate, that is, it can be mathematically 'determined' for design or analysis of concrete. Determinate strength of materials, by definition, can only design or analyse with known values. Fracture mechanics is indeterminate, that is, it is mathematically indeterminate for design and analysis of concrete. Indeterminate fracture mechanics, by definition, can only design or analyse with probability values because of the unknowns.

A simple illustration of this significant difference in the two theories is warranted. Strength of materials will give a determinate value for the amount of reinforcement needed based on strength. Fracture mechanics will give an indeterminate value for the amount of reinforcement needed based on probability. Strength allows reinforcement by one, and fracture mechanics allows reinforcement by many. Equal strength does not mean equally distributed stress. The feature of this analysis is a mathematical basis for equal strength by fibres. The advantage of this analysis is the fibres will be distributed everywhere needed to resist stress and cracking. Conventional reinforcement, meaning mesh or bar, requires cracking some distance through clear cover before being useful. The benefits of the fibres are numerous but ease of construction is easily understood as assurance of proper placement compared to the labour of pre - positioning reinforcement in the field.

Further study of both Table 1 and Table 2 can reveal many other criteria for consideration in projects. There are many features, advantages, and benefits for using both theories and their aspects for the design and analysis of fibre reinforced concrete.

8. Project Results and Discussion

Project concrete is usually specified with a minimum 28-day strength value. Normally with limited concrete project testing data, values within +/- 5% of the mean are considered as not significantly different. Failure is defined as not meeting the project needs and, sometimes, the project wants. Most projects meet the “need” of minimum strength and seldom discuss or meet the “want” of 100% no cracks. Many successful projects have been completed with fibre reinforced concrete behaving as expected.

Core-loc™ specimens are precast specimen for breakwater armour-ing and have conventional reinforcing steel at a nominal ratio for temperature and shrinkage. However, resisting these forces in three-dimensions was a construct-ability challenge. The linear two-dimensional conventional reinforcing was difficult to fabricate, install, and position within these complex shapes. A simple engineering mechanics substitution for the strength of the steel allowed for synthetic macrofiber reinforcing at 5 pounds per cubic yard (3 kilograms per cubic meter). Because of the almost constant exposure to salt water, synthetic materials were an easy choice because no remedial solutions were needed to protect the steel and the easy of use of fibres. One specimen was broken open for two reasons. One reason was for inspection to ensure fibre distribution. The fibres were well distributed. The second reason was to ensure the broken concrete would be held together. Over 6 hours, the specimen was dropped multiple times to separate a piece for inspection. The time and effort needed for the inspection convinced everyone that the fibres would hold the concrete together and contribute to a successful project.

Ramakrishnan and MacDonald cite many other projects with synthetic macrofiber reinforced concrete in the literature, Ramakrishnan 1997. A 1995 - built project compared unreinforced concrete and fibre reinforced concrete. The unreinforced concrete was 23% thicker. The fibre reinforced concrete had crack spacing 4.45 times greater than the unreinforced concrete joint spacing. A 2010 inspection revealed the fibre reinforced concrete crack spacing is now 4.25 times greater than the unreinforced concrete joint spacing. There are many random cracks within the unreinforced concrete panels between joints. The savings in thickness and joint maintenance are significant for the fibre reinforced concrete section of the road project.

Of particular interest is a series of articles in Concrete Construction magazine by Nasvik 2009. Summarizing these articles, there was significantly reduced, essentially zero, curling of the floor with extended joint spacing by the use of a 0.5% dosage synthetic macrofiber. This may also account for the behaviour seen in the project cited above from 1995. Joints are very expensive to maintain and so any reduction in joints is a benefit to the owner and extends the concrete service life.

9. Further Research

Many efforts are underway regarding continuing education for engineers around the world. Back to the fundamentals of engineering is one way to help continuing education and understanding of FRC. The purpose of this paper was to provide some missing basic information about fibre reinforced concrete behaviour. There is no reason for fibre reinforced concrete to be thought of as graduate level only, extremely complicated, or so specialized that only a few understand. The purpose of this paper was to provide a scientific method of approaching this issue with repeatable observations about design and analysis of fibre reinforced concrete by breaking the subject down into easily understood parts. The American Concrete Institute Committee 544, Fiber Reinforced Concrete, has an education sub-committee that is intended to provide further basic understanding that must be supplemented and complemented with project descriptions about why and how fibre reinforced concrete was used.

10. Conclusions

Fibre reinforced concrete is not that complex. Fibre reinforced concrete is understandable if as its name suggests, it is “broken” into understandable pieces. The difficulty in most attempts to understand fibre reinforced concrete is changing scale from the structural behaviour to the material behaviour. Further, comparisons need to be used with which the audience is already familiar. The purpose of this paper is to encourage whatever teaching technique works to provide basic education about the design and analysis of fibre reinforced concrete material properties for project benefits.

Synthetic macrofiber reinforced concrete can reinforce concrete with equivalent strength to other reinforcing materials, with ensured placement and ease of use because of the fibers, and assurances of no corrosion because of their inertness.

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