Book of Abstracts

Monday, 18/Sept/2023

8:30- 9:30am	**Development of structural design Codes for FRC** Location: **Pima,** Session Chair: **Gyorgy Balazs** **FRC in Structural Codes: Novelties and Confirmations in the Forthcoming Eurocode 2 and Model Code 2020** **Professor Marco di Prisco** **Development of the Canadian Bridge Code for Structural Design of FRC Members** **Professor Bruno Massicotte**
9:30- 10:50am	**Session A: Material Properties** Location: **Pima,** Session Chairs **A.E. Naaman, Gyorgy Balazs**
	Session B: Impact and Blast Loading and Ductility Location: **Ventura A** Session Chair: **M. Colombo, M. Khorami**
10:50- 11:20am	**Coffee Break** Location: **Ventura B/C**
11:20- 1:00pm	**Session A: Fiber Distribution and Orientation** Location: **Pima** Session Chair: **Giulio Zani**
	Session B: Fatigue Effects Location: **Ventura A,** Session Chair: **L. Ferrara, Stefan Bernard**
1:00- 2:00pm	**Lunch** Location: **Ventura B/C**
2:00- 3:40pm	**Session A: Mechanical Characterization** Location: **Pima,** Session Chair: **P. Rossi, A. P. Fantilli**
	Session B: Design Specifications for Structural Applications Location: **Ventura A ,** Session Chair: **G. Parra-Montesinos, G. Plizzari**
3:40- 4:10pm	**Coffee Break** Location: **Ventura B/C**
4:10- 5:30pm	**Session A: Temperature Effects** Location: **Pima ,** Session Chair: **Enzo Martinelli, Hassan Aoude**
	Session B: Creep and Long-Term Loading Location: **Ventura A,** Session Chair: **P. Serna, D. Conciatori**

7:00- 9:30pm	**Dinner Monday Night**
Tuesday, 19/Sept/2023	
8:30 - 9:30am	**Application Development** Location: **Pima,** Session Chair: **Giovanni Plizzari** **Application of UHPC Concept in Architectural Precast Concrete** **Dr. Charles Nmai** **Fiber-Enabled Carbon Footprint Reduction in Design and Construction of FRC Tunnel Segments in North America** **Dr. Mehdi Bakhshi**
9:30 - 10:50am	**Session A: High Performance FRC** Location: **Pima** Session Chair: **Bruno Massicotte**
	Session B: Structural Applications 1 Location: **Ventura A** Session Chair: **Jakob Šušteršič, Fausto Minelli**
10:50 - 11:20am	**Coffee Break** Location: **Ventura B/C**
11:20 - 1:00pm	**Session A: Numerical & Computational Modelling** Location: **Pima** Session Chair: **Frank J. Vecchio, Mehdi Bakhshi**
	Session B: Durability and Life Cycle Assessment) Location: **Ventura A** Ssiosen Chair: **Flavio de Andrade Silva** **Session C: Special Online Presentations** Location: **Navajo (240)** Session Chair: **Jean-Philippe Charron**
1:00 - 2:00pm	**Lunch**
2:00 - 4:00pm	**Session A: Structural Rehabilitation and Quality Control** Location: **Pima** Session Chair: **Matteo Colombo, Nicola Buratti**
	Session B: Structural Applications 2 Location: **Ventura A** Session Chair: **Marco di Prisco, Ali Amin**
4:00 - 4:30pm	**Coffee**
4:30 - 6:00pm	**Perspectives and future developments in FRC structural applications** Location: **Pima**
6:00 - 6:15pm	**Closing session** Location: **Pima**

Date: Wednesday, 20/Sept/2023	
9:00 - 11:00am	**Reinforcement for 3-D printing,** Location: **Ventura A** Session Chair: **Narayanan Neithalath** Overview of the procedures and processes for design aspects for 3-D printing reinforcement
	Updating ACI 544-7R Development of Design guide for Precast Tunnel Linings Location: **Ventura B/C,** Session Chair: **Mehdi Bakhshi** ACI 544-7R Overview and Proposed Updates- Tunneling Design and Durability of Underground Structures
	Textile Reinforced Concrete, RILEM TC-292, Location: **La Paz** Session Chair: **Flavio de Andrade Silva** Characterization of Mechanical properties and Development of Design tools for TRC
	Test Equipment for Closed Loop testing of Cement Composites, FRC, TRC, UHPC Session Chair: **GCTS** Closed Loop testing Equipment demonstration by GCTS. Introduction and demonstration of a new test equipment developed for testing FRC, TRC, and UHPC
9:00 - 12:00pm	**A tour of the Laboratory Facilities at ASU Campus,** A walk through the various facilities supporting teaching and research at the ASU Tempe Campus, from Single fiber testing to full-scale structural panels, drop weight impact, high speed tension, and structural fatigue. Materials testing covers a range of Cement chemistry and characterization tests to UHPC, and 3-D Characterization of Mechanical Properties and Development of Test methods for TRC, FRC, and UHPC

Presentation Abstracts

Plenary Session: Development of structural design Codes for FRC

Time: Monday, 18/Sept/2023: 8:30am - 9:30am · *Location:* Pima
Session Chair: Gyorgy Balazs

FRC in Structural Codes: Novelties and Confirmations in the Forthcoming Eurocode 2 and Model Code 2020

Marco di Prisco
Politecnico di Milano, Italy

The current Eurocodes are under revision and estimated to be available in 2025. For the first time in European history, Eurocode 2: "Design of concrete structures" will be extended with a European-wide harmonized annex that covers steel fiber reinforced concrete. The work on Annex L – Steel Fiber Reinforced Concrete started in 2012 and significantly benefitted from the fib Model Code of Concrete Structures 2010. By using the latest scientific findings, the performance classes of Model Code 2010 were integrated in a powerful but easy-to-use design document that covers both ultimate and serviceability limit state for structural engineers. The new Model Code 2020 on existing structures and sustainability uses all types of fibers for generalized concrete to allow integration of the significant toughness in uniaxial tension to be integrated in the resistance equations of conventional concrete, thus guaranteeing a sustainable choice for the reinforcement while emphasizing high- and Ultra-high performance materials and hybrid solutions for the reinforcement.

Development of the Canadian Bridge Code for Structural Design of FRC Members

Bruno Massicotte
Polytechnique Montreal, Canada

The Canadian Highway Bridge Design Code (CSA-S6), for its 2019 edition introduced a new chapter on Fibre-reinforced concrete (FRC) to provide an informative addition to Chapter 8 on Concrete Structures. The Annex specifies requirements for the design of structural components made of precast or cast-in-place FRC with prestressed or non-prestressed reinforcement. It covers the behaviour of tension softening FRC (TSFRC) and tension hardening FRC (THFRC) and considers the design for flexural applications using steel fibres as reinforcement.

The presentation will cover the objectives behind that code development and the direction for new applications. Similarities and differences with other international standards will be highlighted. Improvements are introduced to address the forthcoming 2025 Bridge Code edition along with the anticipated future developments.

MA1_A: Parallel Session A: Material Properties

Time: Monday, 18/Sept/2023: 9:30am - 10:50am · *Location:* Pima
Session Chair: Antoine E. Naaman
Session Chair: Gyorgy Balazs

A Tailored Constitutive Law for UHPC when Exposed to Chlorides and Sulphate Environment to Get Reliable LCA Outcomes

Francesco Soave[1], Davide di Summa[1,2], Nele de Belie[2], Liberato Ferrara[1]
[1]Politecnico di Milano, Italy; [2]Ghent University

The lacking resilience of existing reinforced concrete structures in extremely aggressive environments proves that methods currently employed within the overall structural design framework are unable to guarantee a satisfactory level of safety throughout the structures' service life. For these reasons in recent years, new advanced cementitious materials such as Ultra High Performance Concrete (UHPC) are being developed to resolve this main issue. However, the prescriptive method regularly used to assess durability issues in the practice by design engineer may discourage the use of these innovative materials. In order to overcome this barrier, this paper proposes a new durability-performance design approach which aims to analyse and predict how the structural performance of a system evolves over time, thus providing, based on the attainment of “limit states” a decision-making tool for preventive maintenance, which dramatically affects the overall life cycle environmental impacts and costs. In this paper, a geothermal water collection tank was selected as a case study to demonstrate the advantages of adopting a durability design approach tailored to the use of advanced construction materials and based on performance criteria which encompass the identification of a scenario-dependent and time-evolving constitutive law. The selected tank presents a significant opportunity for improvement due to its exposure to an extremely harsh environment, which according to EN206, can be categorized under both XA (exposure to aggressive chemicals) and XS (exposure to chlorides) exposure classes. This classification is attributed to the elevated levels of chlorides and sulphates found in the water contained within the tank. The research performed and herein reported provides, through the aforesaid constitutive law an assessment of the advantages of using UHPC in extremely aggressive scenarios through a longer maintenance free service life, which serves as an input to establish a comparison of the ecological and economic impacts between the tank built with UHPC and one made of ordinary reinforced concrete.

Validation Of The FRC Uniaxial Tensile Law Proposed By EC2

Matteo Colombo, Giulio Zani, Marco di Prisco
Politecnico di Milano, Italy

The upcoming version of Eurocode 2 is going to introduce design rules also for Fibre Reinforced Concrete and therefore both a classification procedure of the tensile performance ad a uniaxial tensile law is proposed for ULS design of structural members made of FRC. The small changes respect to the tensile law formerly proposed by Model Code 2010 are presented in the paper.

The present work takes advantage of an available database of materials (11 different FRCs) in order to assess the safety level that the proposed law allow to reach when designing structural elements subjected to pure bending. The materials under investigation are all characterized by the use of steel fibres, but differ for fibre geometry, fibre content, compressive and tensile classes.

In particular, for all the materials presented, full-scale tests on beams in bending (with or without traditional reinforcement rebars) are available together with a complete material characterization according to standard bending tests proposed by EN14651 that allows to define the design class for each material according to the proposal of the code.

Design values of the material parameters have been adopted for the definition of the design uniaxial tensile law for each material. A multi-layer plane section analysis approach is then applied to compute the design resistant bending moment of the full-scale beam cross section.

The design prediction obtained can be directly compared with the experimental results in order to assess the safety level of the design approach. A presentation of the results and a critical review of the approach is proposed in the paper.

Identification Of Uniaxial Tensile Laws For UHPFRC Modelling

Giulio Zani, Marco di Prisco
Politecnico di Milano, Italy

Ultra-High Performance Fiber-Reinforced Concrete (UHPFRC) is a composite material consisting of fine-grained concrete and steel fibers that can withstand significant tensile stresses, making it suitable for a wide range of structural applications.

While direct tensile testing provides the most accurate and reliable constitutive behaviors to be adopted in design, difficulties in conducting the tests prompted researchers to develop various indirect methods to determine reliable tensile laws of UHPFRC materials. However, there is still no consensus among the scientific community regarding both the most effective identification approaches and the shape of the discretized post-peak uniaxial tensile response.

In this framework, the paper discusses available procedures for the identification of uniaxial tensile laws for UHPFRC, highlighting their capability to simulate the flexural responses of beam samples. To this aim, parametric analyses and back-calculations based on plane-section kinematic models were applied on flexural tests results of a 19a class material, considering notched (EN14651) beam specimens, as suggested in the most advanced design regulations (i.e. the Model Code 2020). The determination of reliable uniaxial tensile laws for UHPFRC is an essential step in predicting the structural response of this high-performance material and promoting its widespread application in various engineering projects.

The Role of Fiber Orientation: from Standard Beams to the Real Structure

Filippo Medeghini[1,2], Giuseppe Tiberti[2], Giovanni A. Plizzari[2], Peter Mark[1]
[1]Ruhr University Bochum, Germany; [2]University of Brescia, Italy

The mechanical performance of FRC to be used for design is measured through standard tests on small beams, of which the 3-point bending test (according to EN 14651) is one of the most broadly renowned and utilized. Among researchers and practitioners major concerns are being raised about the representativeness of such standard beams for structural design since such beams could have a better overall post-cracking performance than FRC in a real structure. This is due to their geometry and casting procedure which leads to a more favorable fiber orientation along the longitudinal direction. Hence, more and better oriented fibers could be found bridging the tensile crack of the standard beam than in the real structural element. To address this problem, a wide experimental campaign was carried out to compare beams cast according to the standard casting method with beams having different fiber orientations, like isotropic or unfavorable, as typically found in structural elements. Beams with an almost one-dimensional favorable fiber orientation were also tested as an upper bound. The mechanical results are compared with fiber orientation assessments obtained through Image Analysis. This photographic method proves useful to detect the amount and orientation of fibers on a cross-section close to the crack plane of the beams, and a good correlation between mechanical performance and orientation is found. The experimental results show how the standard beams have mechanical performance and orientation values significantly greater than those of typical real structural elements. On this basis, a discussion on the safety factors accounting for fiber orientation is presented.

MA2_B: Parallel Session B: Impact and Blast Loading and Ductility

Time: Monday, 18/Sept/2023: 9:30am - 10:50am · *Location:* Ventura A
Session Chair: Matteo Colombo
Session Chair: Majid Khorami

Impact Strength Of VHPC Thin Panels Reinforced With Synthetic Fiber: Experimental Tests And Numerical Simulations

VINCEZO ROMANAZZI[1], FRANCESCO MICELLI[1], SANDRO MORO[2], PEDRO SERNA ROS[3], MARIA ANTONIETTA AIELLO[1]
[1]University of Salento, Italy; [2]MBCC Group; [3]Universidad Politécnica de Valencia

In past recent years, High-Performance Fiber Reinforced Concretes (HPFRCs) have been studied by researchers for applications in the construction industry. Due to the characteristics of the different mixes, these materials appear to fulfill a large wide of structural requirements in concrete applications. Different authors have investigated the behavior of such materials, by observing that the contribution of fibers may strongly increase the mechanical properties of the plain concrete and in particular its toughness and strain retention in a cracked stage. Strength against impact loads is one of the structural performances that can be increased by adding short fibers in concrete and addressing a proper mix design. This paper reports a research study on a Very High-Performance Concrete (VHPC) reinforced with Synthetic Fibers with Self-Consolidating Concrete (SCC) features. A possible application of the studied materials is referred to panel elements used as building façade. A special concrete mix has been studied, thus the compressive strength had a target of about 110 MPa after 28 days. Three different VHPFRC were realized: one with the addition of polyvinyl alcohol (PVA) microfibers only, the other with polypropylene (PP) macrofibers only and the last one with a mixed combination of these two types of fibers. These mixes, after material characterization, have been used to cast thin square panels without any traditional longitudinal reinforcement, that were tested under impact load. A steel ball was used as impact load, falling from a distance of 1000 mm from the concrete specimens. Differences in the cracking behavior and damage mechanisms, due to the different fibers used in the mix, are illustrated and discussed in the paper. The experimental tests were used to validate a numerical procedure for the prediction of the behavior under impact loads. The same tests have been simulated with a finite element analysis program (ABAQUS) in which the mechanical properties of the mixtures were implemented. A final comparison between the numerical solutions and experimental results is shown in the paper.

Effect of Macro-Synthetic Fibers on the Behaviour of High-Strength Concrete Beams under Blast Loading

Roukaya Bastami, Yang Li, Hassan Aoude
University of Ottawa, Canada

This paper examines the ability of macro-synthetic fibers to improve the behaviour of high-strength concrete (HSC) beams under extreme blast loading. As part of the tests, four beams were tested under simulated blast loads using the University of Ottawa Shock-tube. The tests included two plain HSC beams as controls, and two companion beams built with HSC and macro-synthetic fibers. Each set included beams with and without shear reinforcement to examine shear and flexural response. The effects of the macro-synthetic fibers are studied by comparing the mid-span displacements, blast resistance and failure modes of the beams. The results show the ability of macro-synthetic fibers to improve blast performance in terms of enhanced control of displacements, increased blast resistance and enhanced damage tolerance.

Blast Behaviour of Unreinforced Masonry Walls Retrofitted with Fiber-Reinforced Shotcrete

Jordan Gandia, Hassan Aoude, Murat Saatcioglu
University of Ottawa, Canada

This paper studies the ability of fiber-reinforced shotcrete to improve the blast behaviour of unreinforced masonry (URM) infill walls in buildings. The protective design involved the application of a thin layer of high-performance fiber-reinforced shotcrete on the inside face of an unreinforced concrete masonry block wall. A welded wire mesh was also embedded in the shotcrete to improve behavior. The retrofitted wall was then subjected to gradually increasing

blast pressures using the University of Ottawa shock-tube. The performance of the retrofit was compared to that of a control as-built URM infill wall. The results indicate that the retrofit significantly increased the out of plane blast capacity of the infill wall. The retrofit was also effective in improving the control of blast-induced displacements and reducing the amount of secondary blast fragments.

Ductility in Compression of SFRC and its use with Low CO2 Emissions Green Steel Fibres

Sébastien Wolf[1], Gonzalo Ruiz[2], Angel De La Rosa[2], Elisa Poveda[2], Markus Schäfer[3], Riccardo Zanon[3,4]

[1]ArcelorMittal Fibres, Bissen, Grand Duchy of Luxembourg; [2]ETSI Caminos, C. y P. - Universidad de Castilla-La-Mancha, 13017 Ciudad Real, Spain; [3]University of Luxembourg, Luxembourg, Grand Duchy of Luxembourg; [4]ArcelorMittal Steligence, Luxembourg, Grand Duchy of Luxembourg

This work describes the new compressive stress-strain model for the non-linear analysis of steel fibre reinforced concrete (SFRC) in the new EuroCode 2, Annex L “Steel Fibres Reinforced Concrete Structures” developed within task group CEN TC250/ SC2/WG1/TG2 dedicated to Steel Fibres Reinforced Concrete.

The new model takes advantage of the substantial deformation capability increase given by the fibres reinforcement to any base concrete, providing additional ductility in compression to any SFRC structure. This concept allows to optimize the design of a concrete structure reinforced with steel fibres only, or with a hybrid reinforcement made of steel fibres and rebars. When combining the effect of the ductility in compression with green steel fibres and an optimized concrete mix design, this can lead to substantial economy in terms of CO2 emission for the global structure and gives competitive solutions in accordance with the ongoing trend of reduction of the carbon footprint in buildings. The compression behavior model is grounded on a multivariate analysis that correlates an extensive database of 197 well-documented SFRC compressive tests and 484 flexural tests. This model is very structural engineer oriented considering that the results of the correlations with the database is allowing us to link the flexural performance classes listed in the Annex L of the next generation of the Eurocode 2 and the SFRC compressive strength, which permits a complete classification of any material.

To highlight this positive effect of the model on the design performance, we give an example of the application of the model that shows the enhancement in ductility and strength of a composite steel-SFRC beam section.

MB1_A: Parallel Session A: Fiber Distribution and Orientation

Time: Monday, 18/Sept/2023: 11:20am - 1:00pm · *Location:* Pima
Session Chair: Viktor Mechtcherine *Session Chair:* Giulio Zani

Investigation of Fibre Dispersion in UHPFRC Bridge Girder Using X-Ray Micro-Computed Tomography Analysis

Lakshminarayanan Mohana Kumar, **Stephen Foster**
University of New South Wales, Australia

A case study of monitoring fibre dispersion in Ultra-High Performance Fibre Reinforced Concrete (UHPFRC) structure is presented. UHPFRC continues to gain popularity as a strong, durable, and sustainable material for modern bridge construction. Fabrication of bridge girders using UHPFRC leads to a significant reduction of cross-section and self-weight, partial replacement of conventional reinforcement, and enhancement of shear and impact resistance. However, a common concern with the use of UHPFRC is the influence of casting-induced fibre dispersion on the mechanical performance of these structural elements. Past studies that investigated fibre dispersion focused mainly on laboratory-scale specimens. Studies performed on actual structural members have reported only the biases in fibre dispersion by subjecting cores or prisms extracted along different axes of the structure to tensile tests. This paper describes the nondestructive approach adopted for investigating fibre dispersion in a pre-tensioned UHPFRC I-girder of the Bukit Merah Dam bridge, Malaysia. The concrete consisted of straight and end-hooked steel fibres, each dosed at 1% by volume. X-ray Micro Computed Tomography (micro-CT) analysis of samples cored from uniformly spaced locations on the web was used to map the variation of fibre content and orientation across the girder cross-section as influenced by concrete casting. It is shown that micro-CT with image processing is suitable for the inspection of UHPFRC structural components when a high-resolution, detailed mapping of fibre dispersion is warranted.

New Approaches to Measuring Fibre Orientation in Steel Fibre Reinforced Concrete

Lakshminarayanan Mohana Kumar, **Elias Aboutanios**, **Stephen Foster**
University of New South Wales, Australia

The tensile resistance and crack arresting efficiency of Steel Fibre Reinforced Concrete (SFRC) are determined by the fibre orientation pattern within the concrete, which is highly variable in large SFRC members. The fibre orientation patterns are strongly biased along local concrete flow directions during casting, which varies substantially across regions of a structural member and are often aligned unfavourably with the tensile forces, thereby leading to a weaker tensile resistance. In contrast, smaller prisms used for laboratory characterisation of SFRC typically have a greater fibre alignment with tensile stresses and present a higher resistance as a material property. The paper examines the inadequacy of current practices towards mitigating the uncertainty in the design strength of SFRC members caused by casting-induced fibre orientation. Furthermore, the paper discusses how research progress in the past decade, especially that pertaining to the nondestructive measurement of fibre orientation in SFRC, can be applied to better address this challenge.

Use of X-ray Analysis for the Assessment of Steel Fiber Orientation in SFRC

Matteo Colombo, Giulio Zani
Politecnico di Milano, Italy

The use of non-destructive methods for the identification of the fiber dispersion and orientation in fiber reinforced concrete is a very important point especially for quality control of structural members since an un-proper fiber distribution can significantly affect the material performance and consequently the global structural safety. This paper presents a preliminary experimental campaign of small beams (600 mm x 150 mm x 120 mm), extracted from a larger structural element (beam 3 m long and 50 cm wide) previously tested in bending.

On each sample, digital x-ray technique has been applied to acquire images of the fiber distributions. Each sample has been tested according to a four point bending scheme and the nominal-stress vs crack opening displacement behavior is obtained.

A proper algorithm for x-ray image post-processing based on the 2D FFT approach is applied to assess the fiber orientation within the sample. The results of this procedure in terms of fiber orientation will be discussed and compared with the mechanical performance of the material obtained by bending tests.

The Role of Fiber Orientation: the Way towards Structural Optimization

Filippo Medeghini[1,2], Giuseppe Tiberti[2], Giovanni A. Plizzari[2], Peter Mark[1]
[1]Ruhr University Bochum, Germany; [2]University of Brescia, Italy

Fiber Reinforced Concrete (FRC) structural elements are usually designed by considering orientation factors to account for the possible unfavorable orientation of fibers that reduce material performance. However, fiber orientation could be an opportunity to optimize such performance by exploiting material anisotropy. In this paper, the structural application of a high strength fiber reinforced concrete with a strong one-dimensional fiber orientation is investigated in the field of mechanized tunneling by designing optimized tunnel segments subjected to the TBM thrust jack force. The optimization will be obtained by orienting the fibers in the most favorable way to resist the induced tensile stresses, and by casting the high performance fiber reinforced concrete only in the most critical regions, where maximum stresses arise (i.e. the circumferential joint of the segment or, in a further optimization step, following the curved elastic tension lines which determine splitting and spalling stresses). The rest of the segment will be made of a normal FRC with random fiber orientation. The feasibility of the curved casting methodology, as well as the monolithic behavior of the specimens cast with two different concretes, is experimentally verified through small-scale experiments. Moreover, segments reinforced with traditional rebars, steel fibers and a hybrid solution of rebars and fibers are designed to achieve the same load bearing capacity. The sustainability of the optimized design is addressed through a global warming potential calculation, normalized to the performance of each reinforcement configuration.

MB2_B: Parallel Session B: Fatigue Effects

Time: Monday, 18/Sept/2023: 11:20am - 1:00pm · *Location:* Ventura A
Session Chair: Liberato Ferrara
Session Chair: Erik Stefan Bernard

On The Influence Of Steel Fibers In RC Beams Under Flexural Fatigue Loading

Vitor Moreira de Alencar Monteiro, Daniel Carlos Taissum Cardoso, Flávio de Andrade Silva
Pontifical Catholic University of Rio de Janeiro, Brazil

The present research brings the analysis of the influence of steel fibers on the mechanical degradation of reinforced concrete beams when under flexural fatigue loadings. Current experimental work aims to highlight the potential in diminishing the mechanical degradation of reinforced concrete beams due to fiber addition by effectively maintaining structure stiffness, rebar deformation and crack spacing along the fatigue life. The experimental campaign encompasses two beams with the same reinforcing ratio of 0.35%. While one beam was produced with 50 MPa self-consolidating plain concrete, the other one was fabricated with the addition of 40 kg/m³ of hooked-end steel fibers. The fatigue tests were load-controlled and a sinusoidal wave with a frequency of 6 Hz was applied for the test routine on the pre-cracked beam specimens. The tests were carried on under the same fatigue loading range in order to assess the fiber influence on the mechanical degradation along the cycles. The beams were subjected to fatigue loading until reaching 1,000,000 cycles (run-out) or failure. The use of steel fibers was especially effective in maintaining the structure stiffness under the fatigue cycles. While reinforced beams with steel fiber addition were able to maintain 19 kN/mm along the fatigue test, plain concrete beams presented around 10 kN/mm. The addition of steel fibers also contributes in mitigating the steel strain evolution throughout the time. Therefore, the addition of fibers showed major potential in enhancing the RC structures capacity to resist the fatigue degradation along the structure service life.

Modal Parameters Investigation and Damage Evaluation of Steel Fiber Reinforced Concrete Under Flexural Fatigue Loading

Iranildo Barbosa Silva Junior, Cássio Marques Rodrigues Gaspar, Vitor Moreira de Alencar Monteiro, Deane de Mesquita Roehl, Flávio de Andrade Silva
Pontifícia Universidade Católica do Rio de Janeiro (PUC-Rio), Brazil

Structures may be subjected to static and dynamic loads during their service life. Within the dynamic spectrum the wind, ocean waves and seismic loads are some examples. Thus, the fatigue behavior of concrete materials has received great attention due to cyclic loading that can be of natural occurrence or induced by human activity. The present research aims to investigate the evolution of the modal parameters of steel fiber reinforced concretes under flexural fatigue load and to evaluate how the mechanical degradation can be monitored from a non-destructive impact modal testing over the cycles. Fatigue tests were conducted in the material level on pre-cracked prisms in accordance with the EN 14651 standard. A self-consolidating 50 MPa concrete with hooked-ends steel fibers was developed for this study. Fatigue tests were carried onto a

continuous loading frequency throughout the cycles with a stress ratio of 0.2 and a stress level of 80%. The material's dynamic properties, including natural frequencies, vibration modes, and damping ratios, were tracked to assess the level of damage using modal testing techniques (impact hammer test). It was possible to identify the damage level with the variation of natural frequencies and damping. The Modal Assurance Criterion (MAC) analyses were used to evaluate the sensitivity of damage in the mode shapes. The stiffness degradation showed to be approximately two times higher than the resulting damage obtained with dynamic test and the first flexural mode and the following fifth and sixth vibration modes were more affected along the fatigue test.

Advances in Flexural Fatigue of Cracked Macrosynthetic Fiber Reinforced Concrete: Experimental Performance and Numerical Analysis

Débora Martinello Carlesso, Petar Bajić, Albert de la Fuente
Universitat Politècnica de Catalunya, – BarcelonaTECH, Spain.

With increasing interest in applications of fiber reinforced concrete (FRC) without traditional reinforcement in structures, specific considerations regarding FRC performance under fatigue loads are needed to guarantee the required mechanical performance, durability and compliance with service or limit state requirements. The loss of performance owe to material fatigue-induced strength degradation might be significantly accelerated in cracked cross-sections. This contribution presents results and advances derived from an experimental campaign on the flexural fatigue behavior of pre-cracked macrosynthetic FRC carried out on notched 150 x 150 x 600 mm beams. Fatigue test considered an initial crack width accepted in the ultimate limit state and the evolution of the crack opening displacement and other design-sensitive parameters were monitored and analyzed. A design-oriented constitutive model for predicting the fatigue life in cracking-allowed concrete structures is employed and calibrated for the experimental-studied content (3 kg/m3). These findings are compared and complement previous studies and database on the fatigue behavior of macrosynthetic fiber reinforced concrete.

Cycling Behavior of Concrete Filled Steel Tubes Utilizing Advanced FRC

Ketan Ragalwar[1], Amr Ashraf Soliman[2], Ravi Ranade[3]
[1]New York Power Authority; [2]Degenkolb Engineers, United States of America; [3]University at Buffalo, State University of New York

A concrete-filled steel tube (CFST) is a composite structural member primarily used as a bridge pier or a pile to provide better performance, compared to reinforced concrete, under severe loading conditions such as high-magnitude earthquakes. The recent advances in fiber-reinforced concrete (FRC) can significantly improve the performance of CFST under lateral loadings by leveraging the post-cracking strength and ductility of the material. This study experimentally compares the behavior of CFST specimens utilizing normal concrete (NC), Ultra-High Performance Concrete (UHPC), Engineered Cementitious Composites (ECC), and High Strength High Ductility Concrete (HSHDC). Four half-scale CFST specimens with the above-mentioned concrete infills were tested under lateral cyclic loads to investigate the effect of infill material properties on the structural performance of CFST specimens at increasing drift ratios. The drift ratio was incremented until the fracture of the steel tube of each specimen. The specimens using UHPC and HSHDC achieved significantly higher flexural strengths because of the higher compressive and tensile strengths compared to those using NC and ECC. The specimen using HSHDC achieved the highest structural strength and ductility because of the post-cracking strength and tensile ductility of the material.

MC1_A: Parallel Session A: Mechanical Characterization

Time: Monday, 18/Sept/2023: 2:00pm - 3:40pm · *Location:* Pima
Session Chair: Pierre Rossi
Session Chair: Alessandro Pasquale Fantilli

Effects Of Water-reducing Agent On Rheology And Flexural Performance Of Fiber-reinforced Mortars

Di Qiao, Daisuke Honma, Masaro Kojima
Takenaka Corporation, Japan

This study investigated the effects of the content of polycarboxylic acid typed water-reducing agents on the rheology of steel fiber-reinforced mortars and their flexural performance in the hardened state, aiming for a reliable mix design. The relationship of the rheological properties of fiber-reinforced mortars (water-to-cement ratio 0.3) with fiber content was studied, which was further applied to the fibers of different aspect ratios. Moreover, the resulting flexural performance was examined by three-point bending tests. The test results showed that the effect of increasing the dosage of water-reducing agents on improving the flowability diminishes as the fiber content increases. As for the flexural performance, the influence of the content of water-reducing agents was minor, and a strong correlation with cumulative fiber surface areas was found. However, the one with the highest fiber surface area in this study deviated from such a relationship and showed decreased flexural performance even though its fresh state was acceptable. The confirmed poor fiber dispersion suggests that the incorporable fiber content concerning the mechanical performance could be more bounded than that decided by the fresh state.

Proposed Evaluation Method for Three-point Bending Beam Tests of Fiber Reinforced Concrete

Peter Karoly Juhasz
JKP Static Ltd., Hungary

Fiber reinforced concrete (FRC) is a composite material whose post-crack response is highly dependent on the properties of the mixed fibers, as well as their position and orientation in the matrix and on the fracture surface. To determine the material parameters of fiber reinforced concrete, a relatively small, notched beam with a cross-section of 125 × 150 mm is used in the European test standard. Although a uniform distribution is assumed, this is not the case in the small beam test. The coefficient of variation of the residual test results is usually high, which can be attributed to the relatively small size of the specimen and the random location of the fibers. This large scatter of the results leads to a low characteristic value during the traditional statistical evaluation, which results in an uneconomic design. Furthermore, the fibers were aligned to the longitudinal axis of the beam during production, which also led to an unrepresentative value.

When evaluating material parameters, ignoring the number, distribution, and location of fibers intersecting the fracture cross-section can lead to uneconomical, ineffectual, or even exaggerated material parameters. It is therefore necessary to modify and supplement the actual test standards.

In this paper, a mixing model is presented to determine the number of fibers intersecting the cross-section at a certain fiber geometry and dosage. The effect of mixing is demonstrated using measures of fiber-moment and uniformity. Different methods for the determination of the fiber-moment are presented, and the accuracy and sensitivity of these methods are also investigated. The values obtained are compared with the results of laboratory tests on steel and synthetic FRC. At the end of the experiment, the correlation between fiber-moment and residual strength is presented, along with the correlation coefficients.

A novel extended test method for the evaluation of beam test results using these methods is presented. The method allows more accurate mean, characteristic, and design material parameters to be determined.

Characterisation of 3D Printed Fibre Reinforced Concrete

Eduardo Galeote, Nikola Tošić, Albert de la Fuente
Universitat Politecnica de Catalunya

3D printed concrete (3DPC) is a new and innovative technology capturing the attention of researchers as well as construction and precast companies. Since this construction process allows great freedom of shapes and a high degree of mechanisation, it makes it possible to manufacture elements with complex geometries and optimise construction processes.

However, 3DPC presents certain limitations when compared with conventional concrete manufacturing, such as the use of traditional reinforcement to resist tensile stresses. Given that 3D printing, in the case of contour crafting, uses a robotic arm, placing rebars into the concrete element poses a particular challenge during the printing process. Therefore, alternatives to conventional reinforcement should be considered so concrete elements can successfully resist tensile stresses with the aim of being used for structural purposes.

In this regard, the use of fibres in 3D printed concrete is an increasingly viable option. In this study, different concrete mixes produced with and without fibres were manufactured to analyse the potential mechanical properties that these mixes would be able to achieve. In this regard, short steel fibres have been used to evaluate the residual strength and printability of the material. For this, reference specimens were manufactured by casting concrete specimens. The additives used, mainly superplasticizer to allow for pumpability and carboxymethyl-cellulose to modulate viscosity, provide the material with printability properties and the mechanical tests show that the 3DPC produced is capable of achieving compressive strengths of up to 60 MPa at 28 days and residual tensile strengths of up to 2 MPa.

Mechanical characterization of Ultra High Performance Fiber Reinforced Concrete (UHPFRC) bending behavior

Sara Bascì, Matteo Colombo, Giulio Zani
Politecnico di Milano, Italy

Ultra High Performance Fiber Reinforced Concrete (UHPFRC) is a widely used composite with high strength, ductility, compactness and durability performance, but its mechanical characterization still has some shortcomings. The present paper focuses on the mechanical characterization of tensile behaviour through bending tests, presenting experimental investigations on UHPFRC specimens with a fibre volume fraction of 3.3%. High carbon steel fibres (length equal to 14 mm and diameter equal to 0.2 mm) were included in the high performance cementitious matrix. The material is characterized by a cubic compressive strength of about 150 MPa and average residual flexural strengths fR1 and fR3 equal to 25 MPa and 24 MPa respectively, measured according to the EN 14651 standard. The experimental campaign involves three-point and four-point bending tests on small notched and unnotched beams. Considerations are drawn about the role of the notch and the effects of the test setup on the flexural behaviour in the case of a hardening composite. In addition, particular attention is paid to crack propagation during the hardening phase of the bending behaviour. For a better understanding of the strain evolution, a vision-based measurement tool (Digital Image Correlation) is adopted and discussed in the paper.

Behavior of Reinforced HPFRCC Columns Subjected to Axial and Lateral Loads

Joseph A. Almeida, Matthew J. Bandelt
New Jersey Institute of Technology, United States of America

While widely adopted prescriptive-based design practices work to limit the probability of complete collapse, relatively little attention and emphasis is placed on the damage levels and functionality of structures after seismic events. High-performance fiber reinforced cementitious composites reinforced with steel (R/HPFRCCs) have been of growing interest for such seismic applications to improve structural level damage and performance. In order to progress the implementation of these materials at the structural level, a systematic approach toward understanding the mechanics of R/HPFRCC columns is warranted. Therefore, in this study, an existing numerical framework for R/HPFRCC beams was extended to the analysis of columns across a range of materials, reinforcement ratios, and axial load levels to evaluate the change in component level response. It was observed that axial load can considerably increase the nominal moment capacity of R/HPFRCC columns as well as affect the drift capacity. A shift from failure on the tension side of the element (e.g., reinforcement fracture) to the compression side (e.g., crushing of the HPFRCC) occurs between an axial load ratio of 10 and 20%. Lastly, changes in bond stress due to the material level tensile strength were shown to considerably impact the ultimate component drift capacity.

MC2_B: Parallel Session B: Design Specifications for Structural Applications

Time: Monday, 18/Sept/2023: 2:00pm - 3:40pm · *Location:* Ventura A
Session Chair: Gustavo Parra-Montesinos
Session Chair: Giovanni Plizzari

Influence Of Sectional Design And Fiber Type And Dosage On Cracking Behavior Of Reinforced Beams Made Of Frc

Ignacio Carrascosa[1], Kilian J. Montesdeoca[1], Marc Escrig[1], Marta Roig-Flores[2], Juan Navarro-Gregori[1], Pedro Serna[1]
[1]Universitat Politècnica de València, Spain; [2]Universitat Jaume I, Castellò, Spain

Fiber reinforced concrete is a material that is attracting the scientific community, due to the considerable advantages it brings to reinforced concrete structures in Serviceability Limit States. Even more with its inclusion in fib Model Code for Concrete Structures 2010 (Fédération internationale du béton, 2012), MC2010, which includes a model for crack width calculation that takes into account the "bridging effect" exerted by the fibers that pass through a crack, using for it a parameter that characterizes the residual tensile strength of this material. Numerous authors have analyzed the field of application of this formulation, but there is agreement about it.

The main objective of this work is to analyze the factors that have a major influence on cracking of reinforced concrete beams that include fibers. For this purpose, an experimental program has been proposed, based on the Design of Experiments technique, which includes results of bending tests carried out on 18 beams of 3.70 m length with different reinforcement configurations, fiber type, fiber content and beam height. The results obtained from the tests were analyzed using a Multiple Regression Model, in order to determine which factors are most influential on cracking. Additionally, the results obtained by the model proposed in this work have been compared with those obtained by applying the MC2010 formulation. These results show a mismatch between the experimental results and those estimated by MC2010. Although the approach proposed in MC2010 is coherent, since it has been determined that residual strength of fiber reinforced concrete is the factor that characterizes the effect of fibers on cracking.

Flexural Behaviour and Design of Prestressed SFRC Girders

Bruno Massicotte, William De Broucker, Nicola Cordoni
Polytechnique Montreal, Canada

The paper presents results of an experimental and analytical study on the flexural behaviour of prestressed SFRC girders. An experimental program on five large prestressed SFRC girders was carried out. A self compacting 80 MPa concrete with 1% of fibre content was used. In parallel to the experimental investigation, nonlinear finite element analyses were carried out using EPM3D constitutive model on ABAQUS. Using SFRC tensile properties obtained from centrally loaded

round panels supported on three points in the analysis allowed to capture the beam behaviour. Experimental and numerical results are compared with the prediction of the Canadian Bridge Code CSA-S6-19. The paper suggests guidelines for modelling and designing FRC girders.

Optimization Of Reinforcement For Concrete Tunnel Linings

Ralf Winterberg
BarChip Inc., Japan

Concrete is the main construction material for tunnel linings. Different concrete tunnel lining systems have different reinforcement requirements, and they vary strongly from e.g. initial shotcrete linings to precast segmental tunnel linings. An investigation has been carried out to evaluate the behaviour and performance of the different tunnel lining systems, and their typical structural load-bearing systems have been analysed. In the fame of this work, various published studies have been reviewed and conclusions have been drawn from these studies.

Traditional design methods can underestimate the potential of a tunnel lining system when the models ignore parts of the boundary conditions. Experimental investigations have been carried out to provide data to improve the models and to yield more economic designs of the tunnel linings. Field trials in ongoing projects substantiate and round up the test results while serving to improve the design models. The results of the experimental testing program and the academic research demonstrate that in many cases moderate dose rates of fibre reinforcement can provide the required structural ductility, robustness and safety of tunnel linings while reducing construction cost and time as compared to traditional mesh or rebar solutions.

Crack Width Limit-driven Design of Steel Fiber Reinforced Concrete Structures: a Performance-based Approach for Improving Durability and Sustainability

Danilo Di Giacinto, Ali Pourzarabi, Gerhard Vitt, Hendrik Thooft
Bekaert, Belgium

A simplified SLS design approach for steel fiber reinforced concrete (SFRC) structures is presented here, focusing on refining the tensile law specifically for crack mouth opening displacements (CMODs) less than 0.5 mm. The proposed approach addresses the compatibility issues related to crack widths typically considered for watertight reinforced concrete structures. By incorporating a refined tensile law, the design method seeks to design and verify the watertight performance of SFRC elements in a relatively quick and easy manner for the designer, offering potential advantages in terms of durability and serviceability. It is important to emphasize that this approach is considered a work in progress and invites open discussion within the engineering community. Feedback from industry experts and researchers will be critical to further validate and refine the proposed design methodology. This paper seeks to initiate a constructive dialogue and foster collaboration among professionals to improve the understanding and applicability of SFRC in watertight construction, potentially leading to more resilient and sustainable infrastructure in the future.

Proposal Of An Engineering Design Approach For Non-Metallic Fiber Reinforced Concrete: Through Experimental Study And Numerical Modelling On UHPFRC

Fu Lei Zhou Yang[1], W Serge Auguste Nana[1], Simon Herbe[2], Darja Starostina[2], Jean Nicolas Rovial[2], Emmanuel Bonnet[1], Laurence Trucy[1]

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Without change there is no innovation, creativity, or incentive for improvement, while our future economic growth relies on innovation and competitiveness. Fiber-reinforced concrete (FRC) clearly appears today as a promising mechanical and economical alternative to the conventional reinforcement steel mesh. However, there is still a lack of a unified design philosophy adapted to this material. Model Code 2010 is one of the most widespread design guidelines but established on the basis of steel FRC. Based on the Model Code guidelines, the current Eurocodes are also being revised and for the first time Eurocode 2 will be extended with a harmonized annex covering FRC with metallic fibers but not taking into consideration non-metallic fibers. Non-metallic fibers are taking some of the market share from steel FRC and this is due to their non-negligible performance and ductility in a concrete matrix, their resistance to alkali attack, and their relatively low cost. It therefore becomes essential to be able to rely on design guidelines adapted to these types of fibers because this absence significantly limits their use. In this study, the Model Code recommendations are adapted to the case of non-metallic fibers to provide engineers with simplified tools. A new adapted multi-linear stress-crack opening relationship was proposed, based on experimental studies and non-linear finite element modelling. The Model Code minimum ductility requirements for FRC use in structural applications have also been adapted to the case of non-metallic fibers following Hillerborg's concept of fracture energy and a new proposal of ductility classification was made.

MD1_A: Parallel Session A: Temperature Effects

Time: Monday, 18/Sept/2023: 4:10pm - 5:30pm · *Location:* Pima
Session Chair: Enzo Martinelli
Session Chair: Hassan Aoude

Experimental Tests On The Effect Of Temperature On A Polypropylene Fiber And On A Macro-synthetic FRC

Giorgio Virgulto[1], Marta Caballero Jorna[2], Nicola Buratti[1], Marta Roig-Flores[3], Claudio Mazzotti[1]

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Macro-synthetic fiber reinforced concretes had a rapid diffusion in the construction sector, but despite that some aspects related to their durability are not yet fully understood. Among these there is the effect of temperature on their mechanical behavior in cracked conditions. In fact, both the elastic modulus and the strength of the polymers used to make macro-synthetic fibers are sensitive to temperature variations.

This paper presents the results of an experimental campaign in which tension tests at different temperatures, ranging from 0 °C to +40 °C, were carried out on single fibers and on FRC cylinders. In the tests on the fibers different loading rates were used, to understand the interaction between load rate effect and temperature on elastic modulus and strength. The tests on the concrete cylinders were focused on investigating the effect of temperature only. The paper discusses how the residual strength of the FRC investigated is modified by temperature providing data that might be useful for deriving future design criteria.

An Experimental Study on FRC Subjected to Low (-15 °C) and High (60 °C) Permanent Temperature Exposure

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Steel Fiber Reinforced Concretes (SFRCs) are now spread worldwide, supported by their introduction in standards and codes. However, Macro Synthetic Fiber Reinforced Concretes (MSFRCs) have been excluded in the final draft of the new EC2 despite their common and increasing use. Some properties of Macro Synthetic Fibers are causing mistrust on its capability to reinforce concrete, mainly related with their ageing produced by permanent exposure to temperature. To date, there is little knowledge about the changes of long-term temperature exposure in properties of FRCs, especially MSFRCs.

This research examines the compressive and flexural performance of two fiber reinforced concretes (one MSFRC and one SFRC) to assess their structural capacity when exposed to long-

term permanent temperatures (-15, 20 (reference) and 60 °C) after 90 days of exposure. A modified version of the three-point bending test (EN 14651), was used in order to include an insulating thermal covering which maintain the target temperature constant for all the tests duration. Additionally, this study compares the residual flexural behavior on previously pre-cracked specimens, with cracks produced at 28 days up to 0.5 mm of Crack Mouth Opening Displacement (CMOD) before the exposure at the analyzed temperature.

The results obtained show different trends at low temperature for both FRCs. For temperatures of -15 °C, SFRC presents an increment of their residual flexural strengths with an increase of brittleness; however, for MSFRC, no variations are detected at fR1 while a decrease is detected at fR3. For temperatures of 20 and 60 °C, no significant effects are detected in fR1 and fR3 for both FRCs. Permanent temperature exposure does not also degrade in a critical extent the performance of pre-cracked specimens for both types of FRC, presenting similar outcomes for both states (pre-cracked and non-pre-cracked).

Impact of PVA Fiber on Mechanical Properties of Concrete and Cement Composites

Salam Wtaife[1], Ahmed Alsabbagh[2], Nakin Suksawang[3]

[1]University of Misan, Iraq; [2]University of Information Technology and Communications, Iraq;
[3]Florida Institute of Technology, United States of America

Steel fiber reinforced concrete (SFRC) is becoming more popular in the construction of concrete floors and slabs because of its ability to minimize cracks in concrete. However, one problem with the use of steel fiber is corrosion if the SFRC floors or slabs are exposed to corrosive environments. To avert this problem, other types of fibers such as alkali-resistant glass fiber, cellulose fibers and synthetic fibers have to be used in lieu of the steel fiber. Nevertheless, most these fibers do not have the same ductility as steel fiber. However, one potential steel fiber replacement is Polyvinyl achohol (PVA) that do exhibit strain hardening ability that closely match steel fiber.

In this study, two types of fiber, PVA and steel fibers, with varying volume fractions from 0.5% to 2% were investigated to determine their effect on concrete cracking behavior during the four stages of cracking (namely the elastic and elastic-plastic stages for micro-crack; and service limit and ultimate limit stages for macro-crack) under flexural test. A new analytical method is proposed using a toughness ratio (area of each stage was used to compare the effectiveness of PVA fibers with steel fibers. Results indicated that when sufficient amount of PVA fibers are added to concrete, they could match or outperform concrete with steel fibers at all stages of cracking.

Synthetic Macrofiber: A Material Key to Enhancing the Service Life of Structures

Julie Buffenbarger[1], Michael Mahoney[2], Hessam Azarijafari[3]
[1]Beton Consulting Engineers; [2]Euclid Chemical; [3]University of Michigan

The deterioration of infrastructure has become an increasing challenge and burden on the world's economy, environment, and society. Historically, most structures have been built without durability and service-life consideration, and their premature failure reflects an acute crisis within the construction industry and on the environment.

The inclusion of synthetic macrofiber in concrete structures ensures the maximizing of durability and service life extension and offers potential reductions in the binder content and reinforcing steel materials that contribute to resource depletion, environmental impacts, and increased economic burden. These service life improvements and material reductions present opportunities for housing and infrastructure construction that contribute to protecting the environment and ensuring public safety, health, security, serviceability, and life cycle cost-effectiveness

MD2-B: Parallel Session B: Creep and Long-Term Loading

Time: Monday, 18/Sept/2023: 4:10pm - 5:30pm · *Location:* Ventura A
Session Chair: Pedro Serna
Session Chair: David Conciatori

Long Term Cracking and Deformation Behaviour of FRC One Way Members

Ali Amin[1], Ian Gilbert[2]
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The serviceability performance of structural concrete can be significantly improved through the addition of steel or polypropylene fibers. These benefits are well known in industry and practice. Consequently, several national codes of practice contain well established procedures to predict the strength and short-term serviceability behavior of fiber reinforced concrete (FRC) structures. However, expressions capable of predicting the long-term serviceability behavior of FRC are either not included or provide limited guidance. This limits the full utilization of FRC in design practice. To accurately predict the time dependent deformation and cracking behavior of structural concrete containing fibers, three basic prerequisites are needed: 1. Reliable data for the creep and shrinkage characteristics of a particular FRC mix; 2. Reliable data on the material constitutive, post-cracking, behavior of the FRC; and 3. Reliable analytical procedures which account for any time-dependent deformations that may occur. This paper presents simplified and rationale expressions capable of predicting the long-term cracking and deformation behavior of FRC one-way members. Predictions of the proposed models are compared to available data in the literature and are shown to correlate well.

Creep Relaxation of FRS in the ASTM C1550 Panel Test

Erik Stefan Bernard[1], Ali Amin[2]
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Assessments of creep effects in FRC structures have most commonly focused on predictions of deformation in response to a constant stress or load. This is at least partly because most test data from investigations of creep behaviour, both prior to and after cracking of the FRC matrix, are obtained from specimens subjected to constant stress. However, many FRC structures in practice experience relaxation of stress in response to a constant imposed deformation rather than constant stress. In these situations, the pattern of stress relaxation with the passage of time is the outcome that is sought. The objective of both experiments and modelling is to predict the long-term stress and ongoing deformations in response to a constant imposed deformation.

As part of a preliminary investigation of relaxation in FRC members, a series of ASTM C1550 panels were pre-cracked and subjected to an imposed constant central deformation over a period of two days during which load resistance of the panels were measured. Both steel and macro-synthetic FRS specimens of various dosages were included in the trials, with some of the steel FRS specimens made with moderate strength 32 MPa concrete and some made with high strength 50 MPa concrete. The tests revealed that load resistance fell rapidly over a period of hours for the specimens manufactured with 32 MPa concrete containing either steel or macro-synthetic FRS, but was retained for the 50 MPa steel FRS specimens. Examination of the specimens after testing indicated that the 50 MPa specimens had experienced embrittlement resulting in rupture of the steel fibres rather than pull-out during post-crack deformation.

The results suggest that macro-synthetic FRS and steel FRS in which fibres pull out without rupture exhibit similar post-crack relaxation behaviour characterized by rapid load fall-off, but mixtures in which fibres rupture rather than pull-out are quite resistant to post-crack load fall-off with time as a result of relaxation.

Creep effects in Fiber Reinforced Concrete

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Several international structural codes now include specific chapters dedicated to the design of Fiber Reinforced Concrete (FRC) structures, whose contents are based on several research studies carried out over the years on various design aspects of FRC structural elements. These studies mainly concerned the short term behavior of FRC while its long term behavior, and in particular the so-called “creep” phenomenon, is still a matter of investigation, especially for the significance of standard-test results for structural applications. The complexity of the phenomenon and the approximate way in which it is treated in current standards, together with its importance, especially for structures in service conditions, makes further studies and investigation necessary. When a FRC structural element without conventional reinforcement starts cracking, the equilibrium must be guaranteed by the post-cracking resistance of the FRC and the creep phenomena may play a significant role and, therefore, must be properly taken into account. On the other hand, if traditional reinforcement is present, creep contributes to redistributing stresses from FRC to the rebars and creep phenomena become not relevant when the equilibrium is provided by conventional rebars. The aim of this paper is to discuss the creep effects on the behavior of FRC with polypropylene fibers (PFRC) by evaluating the stress level of fibers in EN 14651 beams and comparing it against the stress level expected in real structures under service conditions.

Correlation of Direct Tension and Short Term Tensile Creep Performances of non-proprietary UHPC

Reid Holland, Michael Ruszala, Hani Nassif
Rutgers Infrastructure Monitoring and Evaluation (RIME) Group, Department of Civil and Environmental Engineering, Rutgers University, Piscataway, NJ

Ultra-high performance concrete (UHPC) has gained popularity in recent years due to its increase in strength and durability over conventional and high-strength concretes. For precast beams, it is capable of achieving a service life of 100 years, and allows for the design of smaller, lighter sections without reducing strength. Its key advantage is its high durability and tensile strength, thanks to its dense matrix and high volume of steel fibers. UHPC also exhibits tensile strain hardening behavior post cracking, further enhancing its durability and strength. Despite its known advantages, a lack of knowledge in testing its tensile behavior withholds it from widespread use. Moreover, there is even less known about its behavior under sustained loading by way of tensile creep, despite the claims regarding its enhanced service life. Tensile creep is not commonly tested for concrete, as conventional design heavily relies on steel reinforcement for tensile properties, causing a lack of a standard testing procedure. This paper presents the results of 4 non-proprietary UHPC mixes in pure tension. Direct tension and tensile creep testing methods are proposed to aide in simplifying testing procedures. A correlation between the short term tensile creep and direct tension performance of UHPC is also assessed to provide greater insight into modelling its tensile behavior for use in design.

Plenary session, Day 2: Application Development

Time: Tuesday, 19/Sept/2023: 8:30am - 9:30am · *Location:* Pima
Session Chair: Giovanni Plizzari

Application of UHPC Concept in Architectural Precast Concrete

Dr. Charles Nmai

Master Builders Solutions Admixtures US, USA, United States of America

Despite being introduced in the early 1990s, the acceptance and use of ultra-high-performance concrete (UHPC) in the U.S. has been a challenge for a variety of reasons. Increasingly though, several state departments of transportation are expressing interest in introducing UHPC in their bridge projects, supported by the Federal Highway Administration (FHWA) research as well as research done by universities. In 2022. The Precast/Prestressed Concrete Institute (PCI) published PCI TR-9-22, "Guidelines for the Use of Ultra-High-Performance Concrete (UHPC) in Precast and Prestressed Concrete" to facilitate technology transfer for the use of non-proprietary cost-effective UHPC as a structural material for precast and precast, prestressed concrete structural members. This presentation will focus on the concept of UHPC in architectural precast concrete applications, including facades and wall panels, using synthetic fibers.

Fiber-Enabled Carbon Footprint Reduction in Design and Construction of FRC Tunnel Segments in North America

Dr. Mehdi Bakhshi

Tunneling and underground projects are at the forefront of practical applications of fiber reinforcement. Virtually all tunnel projects in North America have leveraged fibers for concrete tunnel linings. This includes applications such as precast segmental linings, cast-in-place tunnel linings, and tunnel shotcrete linings. The cost savings are due to expedited production timelines, improved long-term durability, using advanced fiber material properties that have significantly contributed to carbon footprint reduction in these projects.

The economic cost savings are due to shortening of project timelines, Long-term durability, advanced properties of metallic and synthetic fiber technology as well as a combination of cost savings. The advancement of fiber technology has also played a pivotal role. Over the past two decades, the strength of steel fibers has significantly increased, with tensile strength now exceeding 2,300 MPa (333 ksi). These fibers boast advanced designs, help control cracks as narrow as 0.1 to 0.3 mm. Furthermore, synthetic fibers have also made substantial strides in terms of material properties and structural reinforcement capabilities. The availability of codes, guidelines, and standard test methods has also greatly contributed to the adoption of FRC. This talk presents an overview in the complexities of these projects and cover several ongoing projects such as the South Hartford Conveyance and Storage Tunnel (SHCST) in Connecticut, the Pawtucket combined sewer overflow (CSO) Tunnel in Rhode Island, the Montreal Express Link (REM) Airport metro and the Blue Line Extension (PLB) metro tunnel, as well as the Ontario Line South (OLS) metro tunnel in Toronto, Canada. Larger diameter tunnels, such as the 13.5-meter (44.5-foot) Hampton Roads Bridge-Tunnel (HRBT) road tunnel in Virginia, have utilized a hybrid solution of fiber and rebar in their concrete linings.

TA1-A: Parallel Session A: High-Performance FRC

Time: Tuesday, 19/Sept/2023: 9:30am - 10:50am · *Location:* Pima
Session Chair: Bruno Massicotte

Ultra-High Performance Fiber Reinforced Concrete in Tension: Sufficient Strength but Insufficient Strain Capacity

Antoine E. Naaman
University of Michigan, United States of America

This paper mostly relates to the use of steel fibers in strain-hardening Ultra-High Performance Fiber Reinforced Concrete (UHP-FRC) composites; these composites are designed to have compressive strengths exceeding 150 MPa (22.5 ksi) with a volume fraction of suitable steel fibers exceeding about 2%. Current advances in UHP-FRC with steel fibers allow us to state the following: for design purposes, we can count on a direct tensile strength of about 7 MPa (1 ksi), a corresponding equivalent elastic flexural tensile strength of about (2.5 ksi), and a maximum strain capacity in tension for design of 2 to 3/1000. It is argued that, while the nominal tensile and bending strengths seem adequate for many small structural elements made solely from UHP-FRC, the strain capacity is insufficient for adequate structural ductility and safety. Moreover, in hybrid applications with conventional reinforced and prestressed concrete structures, it can be shown that while UHP-FRCs with steel fibers contributes to the service limit states of the structure, they generally do not improve ultimate limit states, such as nominal bending and shear resistance. The key culprit is their current insufficient strain capacity. This is a huge drawback that needs to be seriously addressed by the research community. After an initial discussion illustrating the above limitation by an example, this paper makes the case that the design and selection of steel fibers should include inducing and/or improving slip-hardening bond behavior of the fiber under pull-out, and examining the likelihood of triggering fiber to fiber interlock. Indeed, slip-hardening bond behavior increases strain capacity. The author believes that strain capacities exceeding 10/1000 could be eventually achieved allowing UHP-FRC composites to contribute to the ultimate limit states of reinforced and prestressed concrete structures and, as such, provide a solid justification for their high initial cost.

Shrinkage Influence on the Behaviour of Reinforced UHPFRC Elements

Juan Navarro-Gregori[1], Eduardo J. Mezquida-Alcaraz[1,2], Majid Khorami[1], Pedro Serna[1]
[1]Universitat Politècnica de València, Instituto de Ciencia y Tecnología del Hormigón, Valencia, Spain.; [2]Universidad UTE, Facultad de Arquitectura y Urbanismo, Calle Rumipamba s/n y Bourgeois, Quito, Ecuador.

Shrinkage of concrete can be defined as a reduction in volume through time, mainly due to water movement emptying the porous structure of the concrete, to chemical reactions generating products whose volume is less than the volume of the initial ones, and to the thermal variation during the hydration reactions.. The major concern with regard to shrinkage is the potential for creating tensile strains and consequently the incidence of cracks in concrete. This paper sets out

two separate and complementary objectives. The first objective is to address the experimental results of a specific test method to obtain the free shrinkage value of Ultra-High Performance Fibre-Reinforced Concrete (UHPFRC). The second objective is the study of the influence of shrinkage on the behaviour of reinforced UHPFRC elements. This study is addressed by means of numerical modelling based on the non-linear finite element analysis of reinforced flexural beams and tensile elements. The obtained experimental results for the free shrinkage show a good agreement with the values proposed by codes and guidelines for UHPFRC structural design. Moreover, the results obtained for the numerical modelling show a significant effect of the shrinkage on the serviceability behaviour of reinforced UHPFRC elements. All in all, the consideration of the shrinkage effect of reinforced UHPFRC elements results in an essential design aspect for a correct evaluation of the serviceability behaviour of these structures since a very significant fraction of the UHPFRC tensile strength is retained by the shrinkage effect.

Shear Resistance and Structural Hardening Resistance of UHPC Overlays

Martin Pharand, Jean-Philippe Charron
Polytechnique Montreal, Canada

Ultra-high performance concrete (UHPC) is being increasingly used as a thin overlay for deficient normal strength concrete (NSC) structural elements. Given its remarkable tensile properties, UHPC can provide durable repairs exempt of macrocrack in serviceability limit state as well as significant increase in bending or shear resistance at ultimate limit state. However, its strengthening effect on structures is generally neglected due to the lack of applicable analytical models that can accurately predict the ultimate resistance of hybrid elements.

This paper first describes shear tests conducted on hybrid slabs made of a NSC substrate and an UHPC overlay on the tensile side. The load-displacement curves and digital image correlation (DIC) analysis will highlight the two-stage' structural behavior observed in hybrid slabs: a monolithic action up to the first shear crack occurrence and then a composite action providing structural hardening capability. The paper then introduces new analytical models, complying with the Canadian design philosophy, that predict the shear resistance (VR) of the monolithic action and the structural hardening resistance (VRsh) of the composite action. Lastly, predictions of the analytical models are presented using experimental data retrieve from literature.

Building with Carbon Reinforced Concrete – Challenges and Perspectives illustrated by the C³-demonstration house 'CUBE'

Peter Betz, Michael Frenzel, Steffen Marx, Manfred Curbach
Dresden University of Technology, Germany

Within the framework of the project C³ – Carbon Concrete Composite, an interdisciplinary consortium of more than 160 partners was involved in the research on the composite material carbon reinforced concrete and its application for constructions. The "CUBE" building exemplifies the results of this project, and it is assumed to be the world's first building, constructed entirely of non-metallic, carbon reinforced concrete, which has been completed in 2022. The main purpose of the building is to show that the C³ construction method has progressed so far that the entire process chain can be passed through, including the design, planning, tendering, construction and operation.

This paper presents the complex process for the design and approval of the CUBE, for which a special approval procedure 'ZiE' (consent in individual cases) was required. In particular, the load-bearing structure of individual components, their design and the experiments necessary for their approval are explained and illustrated. Additionally, the resulting advantages over classical building materials are shown and discussed. In general, due to the lack of regulations, this was a time-consuming process that had to be supported by a variety of experiments. However, an outlook is given on the guideline, currently drafted by the DAfStb (German Committee for Reinforced Concrete), which should considerably simplify the design of future structures with carbon concrete in Germany.

All in all, using the example of the "CUBE" building, the article shows a successful, practice-oriented application of carbon reinforced concrete and its diverse and great potential for sustainable buildings in the future, but also the difficulties that must be addressed in order to establish the material.

TA2-B: Parallel Session B: Structural Applications 1

Time: Tuesday, 19/Sept/2023: 9:30am - 10:50am · *Location:* Ventura A
Session Chair: Jakob Šušteršič
Session Chair: Fausto Minelli

Effect of Age on Reverse-Cycle Performance of Hybrid Fibre Reinforced Concrete Beam-Columns

Erik Stefan Bernard, Maurice Guerrieri
Institute for Sustainable Industries and Liveable Cities (ISILC), Victoria University, Australia

Post-crack properties of Fibre Reinforced Concrete (FRC) are known to change with aging. The bond between concrete and steel reinforcement is also known to change as concrete ages, and the strength and elastic modulus of the concrete itself will steadily increase. Given that so many characteristics of both concrete and FRC change with age, it is valid to question whether the reverse-cycle load resistance of RC and RC/FRC hybrid members also changes with the passage of time. Although the effects of environmental exposure, including chloride ion ingress, carbonation, and concrete cracking on the seismic resistance of RC members has been examined extensively, the effect of inherent age-related changes in the properties of concrete and FRC on reverse-cycle load resistance has not received much attention.

To address this short-coming, the present investigation has examined how age-related changes in the properties of macro-synthetic FRC influences the reverse-cycle flexural performance of RC/FRC members. Laboratory testing was performed on conventionally reinforced beam-column members made with plain concrete and macro-synthetic fibre reinforced concrete. A total of 40 beam-columns were tested at ages of 3, 6, 12, 24, and 60 months. The tests indicate that there is a small increase in peak flexural capacity under reverse-cycle loading for both plain and FRC with aging, but that there is no deterioration in post-crack performance with age at least for the MSFRC mixture presently examined. The data also suggest that, when used at practical dosage rates, embossed macro-synthetic fibres can reduce the requirement for confining stirrups by permitting an increase in stirrup spacing. However, previous research using the same reinforcement configuration and test procedure has indicated that fibres cannot replace stirrups entirely. The effect of age and increased stirrup spacing on shear resistance was not included in this investigation.

Assessment of The Performance of Hybrid Reinforced Concrete (HRC) with Polymeric Macro Fiber in Full-scale Precast Panel

chidchanok pleesudjai, Devansh patel, Brazin Mobasher
Arizona State University, United States of America

The use of polymeric macro fibers in concrete matrix, along with ordinary steel rebar reinforcement, known as hybrid reinforced concrete (HRC) can significantly enhance the

performance of concrete structures at the service level. This superior mechanical performance benefits the concrete structures that require more capability in serviceability limit state (SLS) rather than ultimate limit state (ULS), especially for underground structures where the intrusion of water inside the panel can accelerate the corrosion and therefore reduce the durability of a structure. This manuscript presents the results of a full-scale experimental program that investigated the performance, design, and reliability of HRC precast panels for underground water tank structures. A total of five panels were tested with the variable of panel thickness, reinforcement ratios, fiber dosage and rebar combination, and boundary conditions. The central load-deflection response and crack pattern were studied and compared extensively in a controlled environment. The results of this study have been extremely valuable in understanding how fibers diffuse the cracking process and help increase the ductility and durability of concrete when multiple cracks were exhibited in a panel. It is unlikely that one would be able to use the present data and formulate generalized and universal rules in the context of a code language. However, the results are promising enough that a rational evaluation of the results shows the tremendous role fibers can play in increasing service life by enhancing the long-term strength and ductility of concrete precast panels.

Shear Strengthening of Existing 50 Years Old Prestressed Bridge Girders Through UHPFRC

Fausto Minelli

Extended Abstract Available

Numerical Modelling of UHPC Beams With Different Reinforcing Ratios Considering Material Properties

Patrícia B. de Lima[1], Paulo Henrique Marangoni Feghali[1], Daniel Carlos Taissum Cardoso[1], Pablo Augusto Krahl[2], Flávio de Andrade Silva[1]

[1]Pontifícia Universidade Católica do Rio de Janeiro (PUC-Rio), Brazil; [2]Mackenzie Presbyterian University, Brazil

Ultra-high performance concrete (UHPC) is a promising material developed in the last decades that allows design of stronger structural elements. It allies great compressive strength with higher tensile strength compared to conventional concrete (CC) and good durability. Efforts have been made in recent years to understand the reinforcement ratios (RR) effects on UHPC beams. Experimental studies demonstrated that beams with low reinforcement ratios (<2%) result in loss of ductility, which requires further understanding to develop reliable design codes. This study proposes an experimental and numerical approach to optimize UHPC beam sections to resist the same loads as CC beams and present similar ductility. The research shows that the optimized section results in about half of the CC cross-section. The finite element model explores a new methodology in which the variability of the material is taken into account in the discretization of the structural element, resulting in strain localization of the beam failure.

TB1-A: Parallel Session A: Numerical & Computational Modelling

Time: Tuesday, 19/Sept/2023: 11:20am - 1:00pm · *Location:* Pima
Session Chair: Frank J. Vecchio
Session Chair: Mehdi Bakhshi

Structural Response of FRC Onshore Wind Turbine Shallow Foundations: a Numerical Investigation

Paolo Martinelli, Matteo Colombo, Marco di Prisco
Politecnico di Milano, Italy

On- and off-shore wind turbines are an important strategic infrastructure for the production of electricity from renewable energy sources and their increasing deployment favors decarbonization. A key component of onshore wind turbines is the foundation that represents a massive structure where the large volume of concrete requires large amounts of reinforcement. The design of these massive elements is not an easy task as they are not specifically addressed in technical Standards. In this context, a numerical/experimental research program between Politecnico di Milano and Enel Green Power Spa was recently concluded. One of the main objectives of the research was the possible reduction of reinforcement bars obtainable by using steel fibers with a consequent increase in execution speed and greater competitiveness. The experimental program comprised a total of six 1:15 scale soil-foundation-tower specimens, two of which were produced in fiber-reinforced concrete (FRC). The paper intends to present the results of numerical analyses aimed at understanding the structural behavior of FRC foundations. Finite element numerical analyses are conducted using three-dimensional elements for both concrete foundations and soil and one-dimensional elements for steel rebars. Combined complex phenomena, such as soil-structure interaction, material nonlinearities, and local stress concentration in both reinforced concrete foundation and soil are treated.

Parametric Numerical Study on Jointless Macro Synthetic Fiber Reinforced Concrete Industrial Floors

Peter Schaul[1,2], Karoly Peter Juhasz[2]
[1]Budapest University of Technology and Economics, Hungary; [2]JKP Static Ltd.

The demand for jointless industrial floors is increasing, but there are no relevant agreed-upon standards or design recommendations, particularly for floors made of synthetic fiber reinforced concrete. The primary challenge associated with jointless floors is controlling the cracking caused by the restrained movement of concrete due to shrinkage and temperature changes. In addition to predicting the stress and cracking that will arise from service loads, investigation of long-term effects requires significant attention. This study conducted a parametric numerical analysis of industrial floors, with typical joint spacings ranging from 6 to 25 m and a thickness of 200 mm evaluate long-term shrinkage and temperature effects under typical load conditions (Uniformly

Distributed Load, UDL). Numerical studies were conducted using the ATENA finite element software, with the effects of fibers was modeled using the modified fracture energy method. The main goals of this study were to develop a practical design methodology and define the maximum acceptable crack-width during the lifetime of the floor. Additionally, the relationships among the geometrical dimensions, material properties, and loads of an industrial floor were depicted as a diagram, which can serve as a reference for designing joint distances.

Numerical Analysis of Steel Fiber-reinforced Concrete Beams Based on Analytical Models for Predicting the Residual Flexural Strength

Vinicius Costa Correia, **Aline da Silva Ramos Barboza**
Federal University of Alagoas, Brazil

Fibres are known to improve the performance of concrete in post-cracking behavior, particularly in terms of mechanical properties such as tensile strength, flexural strength, and toughness. The residual flexural strength parameters (fR1, fR2, fR3 e fR4) and the limit of proportionality (fL) are the basis of fiber-reinforced concrete (FRC) characterization and specification. The use of analytical models for the prediction of these parameters facilitates the design process of FRC structures, since the performance of experimental tests demands cost and execution time. In this context, this paper aims to carry out a numerical analysis via the finite element method (FEM) of steel fiber-reinforced concrete (SFRC) beams, which allows establishing the prediction of residual flexural strengths from equations proposed in the literature, without the need for a large trial campaign. The constitutive relationship of SFRC is made by means of the plastic damage model Concrete Damaged Plasticity (CDP), when a nonlinear behavior of the composite is adopted. To validate the applicability of the model, a numerical validation was performed, modeling and simulating in ABAQUS the flexure test on SFRC beams. The beams have mean concrete compressive strength (fcm) equal to 43.6 MPa, with fiber contents of 25 and 50 kg/m³. Regarding the characteristic length (lcs), two analyzes were performed, the first assuming lcs equal to 50 mm (fiber length) and the second considering lcs equal to 150 mm (beam height). In general, the numerical results indicated a good correlation with the experimental results, thus validating the SFRC modeling performed in this work.

Numerical Designing of Fibers Reinforced Concrete Eco-Constructions

Pierre ROSSI
Pierre Rossi Consulting, France

This paper focuses on the use of numerical tools, as a finite elements method, to conceive fiber reinforced concrete (FRC) eco-constructions. It highlights the fact that these are the most suitable tools (much more than the Eurocodes, for example) to predict the cracking process of FRC constructions at their service limit state and, therefore, to predict their durability. Following a critical analysis of the existing finite element models for FRC cracking, it describes in more detail a probabilistic one. This model appears very suitable for providing precise information about crack openings that are inferior or equal to 300 microns. Finally, it presents an example of the use of this numerical model to optimize an FRC track slab in order to reduce its carbon footprint.

This study, although partial and incomplete, shows that the best way to reduce the carbon footprint of this type of construction is to reduce its thickness.

TB2_B: Parallel Session B: Durability and Life Cycle Assessment

Time: Tuesday, 19/Sept/2023: 11:20am - 1:00pm · *Location:* Ventura A
Session Chair: Flavio de Andrade Silva

Sustainability And Constructability Aspects Of Track Slabs Using Fiber-reinforced Concrete

Devansh Patel[1], Chidchanok Pleesudjai[2], Barzin Mobasher[3]
[1,2] Graduate Research Associate, [3]Professor, School of Sustainable Engng & Built Env. Arizona State University, Tempe, AZ, USA,

The efficient utilization of materials and the ease of construction are critical factors influencing the design methods employed in concrete structures. The ultimate objective in the development of new construction materials is to create sustainable, durable, and robust materials along with their corresponding design procedures. During the process of expanding the service track lines and adding multiple stations, the City of Phoenix encountered significant resistance in 2019 due to the projected cost and duration of the proposed project. To address these concerns, a design utilizing fiber-reinforced concrete (FRC) track slabs was proposed and tested as a viable, cost-effective, and time-saving construction solution for the light rail extension, satisfying the requirements of the City of Phoenix and Valley Metro Transportation Authority. Arizona State University (ASU) played a crucial role by assisting in the design, analysis, and testing of mockup specimens of two types of slabs: one utilizing the original dimensions with reinforced concrete, and the other with using FRC. The performance of fibers in track slabs was evaluated through flexural tests conducted on full sections, as well as fatigue testing simulating the entire lifespan under service load conditions. The results indicated that the utilization of steel fibers with a dosage of 38.5 kg/m3 significantly improved ductility and extended the service life to 2 million fatigue cycles. Furthermore, the ease of construction associated with FRC demonstrated a profound impact on constructability and sustainability.

UHPFRC Permeability to Chloride under Service Load

Vicky Turgeon-Malette[1,4], Nathalie Kamileris[1], Samaneh Khani[1], David Conciatori[1], Xuande Chen[1,2], Thomas Sanchez[1,3]
[1]Université Laval, Canada; [2]Université du Québec à Rimouski, Rimouski, Canada; [3]Université de Lyon, Lyon, France; [4]EMS, Québec, Canada

The effect of multiple microcracks on the chloride diffusion coefficient is critical to guarantee the design lifetime of Ultra-High Performance Reinforced Concrete (UHPFRC) under service conditions. Static four-points bending tests (4PBT) were carried out on UHPFRC beams to characterize its mechanical properties and cracking evolution and the tested beams were made

of UHPFRCs containing 2% volume of stainless-steel fibers. A special test set-up was designed to apply and maintain a sustained bending moment on the UHPFRC beams. The service load was represented by spread microcracks in UHPFRC beams before reaching the maximum load. All cracks were monitored by Digital Image Correlation (DIC) during the loading process. Chloride ion permeability evaluation was measured with a sustained load or without load by a modified procedure of the accelerated migration test, after which chloride profiles were obtained from grinding tests. A 2D Finite-Element-Method model considering both moisture transport, multi-ionic diffusion, coupling effects of temperature, electrical field, and ionic force in its governing equations was adopted to simulate the process. All cracks were integrated in the mesh with adjusted diffusion coefficients according to crack widths across the mesh. The results contained different chloride penetration rates and chloride profiles in tested UHPFRC beams and simulation graphs under different loading levels. The influence of the microcrack width was clearly identified on the apparent chloride diffusion coefficient of the considered UHPFRC. All these results are precious information for a better prediction of the service lifetime of a UHPFRC structure.

Application of Life Cycle Assessment in the Analysis of Environmental Impacts of Fiber Reinforced Concrete

Iva Emanuelly Pereira Lima, Aline Silva Ramos Barboza
Federal University of Alagoas, Brazil

The use of fiber reinforced concrete (FRC) has been gradually increasing world wide and has undergone several advances. From this, the use of this type of concrete for structural purposes has been consolidated over the last 15 years, however, little is known about the environmental impacts that the implementation of this type of alternative can have on the environment. Thus, in order to analyze the environmental impacts caused by the use of the FRC, an analysis of these impacts can be carried out through a life cycle analysis (LCA). Based on this problem, the present work aims to carry out a comparative study of the life cycle analysis (LCA) of a sample of fiber reinforced concrete beams (FRC) with a sample of conventional concrete beams (CC), where both composites were produced for later structural application. For this, the CML baseline was used as the Life Cycle Impact Assessment (LCIA) method and the concrete mixes were entered into the OpenLCA software. Also, the system boundary was of the cradle to gate type and the m^3 of concrete produced and the m^3/MPa of concrete produced were used as functional units. According to the study carried out, it was verified that, for the analysis of the results per m^3 of concrete, despite very similar values, the CC presented less potential to cause impacts, however, for the analysis of the m^3/MPa of concrete produced, FRC performed better. Therefore, it was verified that, even with the expenses related to fiber transport, there is a positive balance in the production of FRC. This shows that, when compressive strength was added as a performance indicator, the FRC presented more satisfactory results of environmental impacts.

CARBOrefit®: Strengthening of Steel-Reinforced Concrete Structures with CRC in Germany

Peter Betz[1], Alexander Schumann[2], Manfred Curbach[1]
[1]Dresden University of Technology, Germany; [2]CARBOCON GMBH

There are a lot of challenges to overcome with existing structures, and the complexity of the measures is often greater than with simple new buildings. In the case of listed buildings (monuments) in particular, it is important to maintain or restore the load-bearing capacity as well as the external appearance. One method that offers a number of advantages is the strengthening with carbon reinforced concrete (CRC). Thanks to the thin layer thicknesses, even filigree structures can be retained without a decisive interference in the appearance. In addition, a lot of extra weight can be saved and the moisture introduced can be reduced. This is ideal not only for monuments, but for steel-reinforced concrete structures in general.

Strengthening of steel-reinforced structures with CRC in Germany is regulated by a general building approval (abZ) issued by the German Institute for Building Technology (DIBt). This so called CARBOrefit® method (formerly TUDALIT®) can be used without the need for individual approvals, which offers a cost-effective, fast and simple solution to strengthen existing reinforced concrete structures.

Based on current examples of application the procedure, implementation and results of this method are shown. Therefore, an overview of the individual components and the performance of the method is given. Also, the minimally invasive treatment of the substance and thus the compatibility with the protection of historical monuments is presented. The article calls for greater use of these processes and thereby to contribute to the protection of our environment, as an extended operating lifespan of buildings helps preserve a considerable number of resources.

TB3_C: Parallel Session C: Special Online Presentations

Time: Tuesday, 19/Sept/2023: 11:20am - 1:00pm · *Location:* Navajo (240)
Session Chair: Jean-Philippe Charron

Experiences With the Design and Structural Verification of GFRC Parapet Elements

Alejandro Nogales, Andrea Monserrat, Albert de la Fuente
Technical University of Catalonia, Spain

The use of fibre reinforced concrete (FRC) increased significantly due to the publications of models for its design in codes and design guides. Fibres are used for either partially or totally substituting conventional reinforcement in structural members (tunnel linings, slabs, foundations, etc). In recent years, the combination of FRC with high performance concrete (HPFRC) has revolutionised the precast industry and opens a new window for a vast range of architectural element design. HPFRC allow designing new architectural and street furniture elements for aesthetical purposes with complex shapes, which are hard to reach with traditional reinforced concrete or non–competitive from an economic point of view. In this regard, this research contribution presents the structural verification of two architectural elements made of glass fibre reinforced concrete (GFRC): ceiling panels and balcony parapets, for a residential building in Barcelona. Ceiling panels were tested experimentally whereas balcony parapets were numerically assessed by means of non-linear finite element simulations.

Macro Synthetic Fibre Reinforced Concrete at Elevated Temperatures

Todd Clarke[1,2], Sam Fragomeni[2], Maurice Guerrieri[2]
[1]BarChip Australia Pty Ltd; [2]Victoria University, Australia

A constant requirement in modern construction contracts is the requirement for adoption of sustainable alternatives. This is driven by the latest outcomes from the 27th UN Climate Change Conference of the Parties (COP 27) challenging society that more needs to be done to drastically reduce emissions now. While the push for sustainable alternatives is necessary, it must also be balanced with safe adoption of new materials in design and construction. Macro synthetic fibres are one such material gaining acceptance in the market as they provide a more sustainable reinforcement offering in many applications. However, current applications are limited due to the lack of knowledge on the response of macro synthetic fibre reinforced concrete (MSFRC) when exposed to elevated temperatures. While some research has been conducted in this area, no generally accepted consensus on the residual performance of MSFRC subject to elevated temperatures exists.

This paper aims to provide a summary of a recently published systematic literature review on the behaviour of macro synthetic fibre reinforced concrete and compare it to early results from a comprehensive research project currently being undertaken at Victoria University. The review proposed relationships between residual strength and temperature for critical properties of MSFRC such as compressive strength, tensile strength, elastic modulus and residual flexural

tensile strength. Comparison against early experimental results provides validation for some of the relationships proposed in the review, while providing context against the currently accepted relationships defined in EC2 for plain concrete.

Structural Response Evaluation of Ultra High-Performance Fiber Reinforced Concrete Beams under Shear

Roya Solhmirzaei[1], **Venkatesh Kodur**[2]
[1]Louisiana Tech University; [2]Michigan State University

Ultra high performance fiber reinforced concrete (UHPFRC) offers benefits including high compressive and tensile strength, enhanced ductility, improved post-cracking response, and tensile strain-hardening characteristics. These outstanding properties of UHPFRC result in improved shear resistance, leading to the possibility of removing shear reinforcement in UHPFRC beams. This study aims to evaluate the ability of UHPFRC to sustain its strain-hardening characteristics under shear at structural level. On this basis, four beams are tested under dominant shear loading. The test variables include sectional properties, longitudinal reinforcement ratio, and presence of shear reinforcement. Further, a finite element-based numerical model is developed and validated against experimental data obtained from tests on UHPFRC beams. A set of parametric studies is conducted to evaluate the effects of governing parameters on shear response of UHPFRC beams, and to explore the feasibility of removing shear reinforcement. The results indicate that steel fibers significantly improve the load-carrying capacity and post-cracking stiffness in UHPFRC beams. It is also revealed that UHPFRC beams without shear reinforcement subjected to dominant shear loading, can attain ultimate load capacity without experiencing brittle failure before rebar yielding. This behavior is attributed to the enhanced tensile strength, ductility, and improved cracking response of UHPFRC with tightly controlled crack width which is facilitated by fibers bridging at the crack surfaces.

Influence of Low Temperature on the Post-cracking Behaviour of Fibre Reinforced Concrete: Experimental and Numerical Investigation

Alejandro Nogales, Stanislav Aidarov, Albert de la Fuente, Nikola Tošić
Technical University of Catalonia, Spain

The use of fibre reinforced concrete (FRC) for structural purposes partially or total substituting the traditional rebar reinforcement has significantly grown. This is an attractive solution since the construction sector increases yearly and the use of fibres brings the opportunity to optimise the reinforcement, leading to a lower material consumption, cost reduction and driving to a more sustainable industry. Despite comprehensive research has been done on the technology, few studies focused on the behaviour of FRC exposed to low temperatures, of great importance in cold regions where structural elements are exposed to extreme temperature conditions. Concrete under low temperatures has proven to improve its mechanical properties and, with

this in mind, this research contribution presents an experimental programme to assess the influence of low temperatures on the post-cracking behaviour of FRC by carrying out three–point bending tests. The specimens cast with synthetic fibre reinforced concrete (MSFRC) and steel fibre reinforced concrete (SFRC) with fibre amount of 8 kg/m3 and 30 kg/m3, respectively, and are exposed to a range of temperatures from 20oC down to -30oC. Furthermore, back–analyses are performed by means of finite element analyses to derive empirical adjustments in order to take into consideration the possible effects of temperature in the tensile constitutive equation proposed in the fib Model Code. The results from this experimental programme are the basis for future experimental and numerical research to improve the design of FRC structures subjected to low temperatures during service life.

Flexural Behavior of Steel Fiber Reinforced Concrete Slabs: Experimental and Numerical Investigation

Stanislav Aidarov, Alejandro Nogales, Nikola Tošić, Albert de la Fuente
Universitat Politècnica de Catalunya, Spain

Fiber reinforced concrete (FRC) has proven to be a suitable material for elevated flat slabs, and already constructed FRC slabs with partial or even total substitution of reinforcing steel bars in office and residential buildings are a supporting evidence for that statement. However, the application of FRC technology is still limited in elements with high structural responsibility because of a number of factors related to the general comprehension of the material's properties and design approaches. With this in mind, an experimental program was carried out in order to evaluate the flexural behavior of three FRC slabs (3.0 × 3.0 × 0.1 m3) subjected to point load under a statically indeterminate test configuration. The results derived allow highlighting the significant flexural strength, redistribution capacity, and ductile response of the studied elements. Thereafter, the constitutive model was derived based on the results of three-point bending tests (3PBT) on notched beams; those were tested to characterize FRC used. The model was considered to simulate the behavior of analyzed FRC slabs by means of nonlinear finite element analysis. As a result, a considerable overestimation of the flexural response was observed. Thus, a feasibility of using the constitutive models that are derived from a 3PBT to numerically assess the behavior of statically indeterminate slabs is among the questions that shall be further studied.

Tensile Stress Versus Strain Response Of Textile Reinforced Cementitious Composites (TRCCs) At Both Static And High Strain Rates

Van Doan Truong[1,2], Dong Joo Kim[1]

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This paper summarized several recent studies about the investigation of tensile stress versus strain responses of textile reinforced cementitious composites (TRCCs) at both static and high strain rates. Experimental conditions, including test machines, test setups, specimen geometry and size, for measuring the direct tensile response of TRCCs at both static and high strain rates, were carefully reviewed. The specimens with the widened ends successfully prevented the pull out of textile from mortar matrix and the cracks at grip parts. The width between 40 and 100 mm, thickness between 6 and 30 mm, and length at least 50 mm were appropriate for the tensile specimens of TRCCs. Soft clamping grips, including the wedges and bolted-clamping system, and steel flanges clamping grip, produced higher bond strength between textile and mortar matrix than clevis grips. Linear variable differential transformers (LVDTs) and digital image correlation (DIC) were suitable for measuring the elongation and strain distribution of specimens, respectively. Based on the analysis of experimental conditions, tensile test setup and specimens were proposed for measuring the tensile behaviour of TRCCs at both static and high strain rates. A bell-shaped specimen was proposed for the tensile tests while a universal testing machine (UTM) and an improved strain energy frame impact machine (I-SEFIM) was used for tests at static and high strain rates, respectively. The hinged grip, categorized as soft clamping grip, was recommended for tensile load transfer mechanisms rather than the bolted-clamping grip because the hinged grip was more straightforward and faster to implement in testing procedure than the clamping ones. Then, high strain rates effects on the tensile response of glass TRCCs (GTRCCs) and carbon TRCCs (CTRCCs) were investigated by using the proposed test setups. At static rate, GTRCCs, using glass textile (GT) with a sufficient bond produced a trilinear tensile behaviour, whereas CTRCCs, using carbon textile (CT) with insufficient bond in mortar matrix, produced a bilinear tensile response. However, at high strain rates, both GTRCCs and CTRCCs have shown tensile strain hardening response. GTRCCs exhibited higher rate sensitivity than CTRCCs. The interfacial bond strength between textile and mortar matrix was found to be a main factor of the high-rate sensitivity of GTRCCs under tension. Short fibers, developing the cross-link between textile and matrix and improving the overall bond of reinforcement within mortar matrix, significantly enhanced the high-rate sensitivity of GTRCCs under tension.

TC1_A: Parallel Session A: Structural Rehabilitation and Quality Control

Time: Tuesday, 19/Sept/2023: 2:00pm - 4:00pm · *Location:* Pima
Session Chairs: Matteo Colombo, Nicola Buratti

Additive Manufacturing For The Regeneration Of Existing Tunnels: a New Slip-forming Technique Using FRC

Andrea Marcucci[1], Stefano Guanziroli[2], Liberato Ferrara[1]
[1]Politecnico di Milano, Italy; [2]Hinfra ltd., Casale Monferrato, Italy

In the recent years the implementation of Additive Manufacturing (AM) technologies in concrete construction industry has been gaining great potential and momentum due to the necessity of enhancing the productivity and innovation uptake of the sector and making it more and more aligned with the evolving needs of the society. In this framework this paper presents the validation through full scale tests, of a slip-forming methodology for the refurbishment of existing tunnels, developed by Hinfra ltd., which employs extrudable steel fibre reinforced concrete (SFRC). This method provides an innovative framework for the maintenance interventions of highways and railways tunnels. Along with the description of the slip-forming process, the purpose of this paper is to provide a framework for the assessment and monitoring of an “as-built” full-scale 3D printed SFRC tunnel segment, that consists of non-destructive assessment of the fibre-dispersion , followed by a full scale structural test on a tunnel segment mock-up, complemented with usual characterization tests performed at the material level. The structural tests have been performed at the ELSA laboratory of the European Commission Joint Research Centre in Ispra in the framework of the OPENLAB ETRL project and are meant as a preliminary validation of the employed design criteria as well as of the effectiveness and structural soundness of the proposed technology.

Early Age Fracture Behaviour of Extrudable FRC for Tunnel Retrofitting: Material Characterization and Structural Transient Design Verification

Andrea Marcucci[1], Stefano Guanziroli[2], Liberato Ferrara[1]
[1]Politecnico di Milano, Italy; [2]Hinfra ltd., Italy

The automation of construction, one of whose benefits is surely enhanced productivity, implies structural materials, concrete the foremost among them, to be subjected since very early ages and during the transient stages of the construction development to combination of actions which may be close to the persistent design situations. In the case of concrete and cementitious composites, whose performance evolves over time because of binder hydration, the determination of mechanical properties and design parameters in early and even very early ages may henceforth be crucial, on the one hand, to design the same automated construction process and, on the other, to check the strength and stability of the artefact in the same stages. Vertical

and horizontal slip-forming are a remarkable and nowadays quite common example of what above said, in which concrete at a mere few hours of life is called to withstand the self-weight of the just built structural parts and of those progressively interacting with it. In this paper the case study is presented of a new slip-forming technique for tunnel retrofitting and/or new construction, in which, due to the scheduled productivity of the system, Fibre Reinforced Concrete (FRC) tunnel linings of a mere few hours age has to start withstanding their self-weight as well as interacting with the existing lining. A tailored material characterization has been undertaken for the purposely designed extrudable FRC, whose design parameters, as per fib Model Code 2010, have been identified at 4 hours, 8 hours, 24 hours and 72 hours, together with more “customary” deadlines of 7 and 28 days. A “stabilization” of the toughness properties of the material has been observed after 24 hours, together with a remarkable deflection hardening performance since the first hours, whereas, as well known from the literature, the compressive strength continued to grow over time according to predictable trends. The design parameters identified as above has been henceforth employed to construct design Moment-Axial force interaction domains and moment-curvature sectional diagrams. These have allowed to design the transient design stages of tunnel linings of varying thickness and identify the progressively evolving level of safety for transient design situations in which the same lining has to withstand its self-weight and start interacting with existing lining to allow the construction to proceed as scheduled.

Correlation Between The Barcelona Test And The 3-Point Bending Test On Three Fiber-Reinforced Concrete Slabs

Bruno Leporace-Guimil[1], Antonio Conforti[2], Nikola Tošić[1], Sergio Carmona[3], Albert De La Fuente[1], Giovanni Plizzari[2]

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This paper evaluates the Barcelona Test (BCN test) and inductive method as techniques for assessing the mechanical behavior of Fiber-Reinforced Concrete (FRC) and provides a simple, efficient, and accurate method for quality control of FRC. Characterizing FRC’s post-crack behavior is crucial for proper design and application. The presented techniques’ results have less scatter and require less material and time consumption than other methods. In this context, this experimental campaign aims to establish a correlation between BCN results and the commonly used 3-point bending test (i.e., EN 14651), which is widely accepted as the reference for characterizing FRC and developing design equations. Therefore, a collaborative study was conducted by the University of Brescia (UniBS), the Polytechnic University of Catalonia (UPC), and Federico Santa Maria Technical University (FSMTU) using 428 cylindrical samples extracted from 3 slabs (250 x 250 x 15 cm), reinforced with 50 kg/m3 of Steel Fiber-Reinforced Concrete (SFRC). These slabs were previously cut orthogonal or parallel to the cast direction to obtain 192

small beams (15 x 15 x 55 cm) and characterize their post-residual strength according to EN 14651. Results showed the strongest correlation between tests and offer a convenient and dependable method for quality control of FRC through the BCN test. In addition, the inductive method has been carried out on the cylinders before the BCN test since it is a Non-Destructive Test (NDT), which is an easy, fast, and effective test that aims to estimate the dosage of steel fiber and its average projection of the fibers for each axis in the cylinders. This method provides both localized and average values, allowing for a more comprehensive understanding of the fiber distribution inside the concrete element. This information could be invaluable for the design and construction processes as well as for understanding the special behavior between concretes with the same average fiber distribution.

Statistical Optimization of FRC Quality Control

Eduardo Galeote, Andrea Monserrat, Albert de la Fuente
Universitat Politecnica de Catalunya

The use of fibre reinforced concrete (FRC) has more presence than ever before in construction projects. The possibility of using fibres as a partial or total substitute for conventional reinforcement makes this material an increasingly popular alternative. For this, even though codes and international guidelines provide recommendations associated with the residual strengths for traditional reinforcement replacement, construction projects also establish minimum strength requirements FRC needs to meet.

The residual strength of FRC is usually determined through bending tests, which is generally associated with great variability in their results. Such variability significantly reduces the characteristic strength of the material with respect to the average strength result, which may result in characteristic residual strength not reaching the minimum strength criteria established in the project. This issue may lead to the rejection of concrete batches and jeopardise concrete production.

Consequently, tests with lower variability, such as the Barcelona test (Double Punch Test, DPT), are being used for determining the residual strength through correlations between tests so that an alternative test can be used to reduce the variability of the results and the number of rejected mixes. In this study, a statistical approach is presented to assess the influence of the variability of the test on the acceptance requirements. Considering a pre-defined characteristic strength, the study aims at defining the number of tests to be conducted per each concrete set manufactured and determining the volume of concrete to be tested.

This study provides a methodology to simplify the quality control of FRC, taking advantage of more efficient and representative tests. The analysis through statistical variation allows defining a strategy to define and optimize an FRC quality control procedure to minimize the number of rejected concrete batches.

Crack Width and Rebar Corrosion in RC and R/FRC Ties Subjected to Cyclic Loads

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In the tensile zones of reinforced concrete (RC) structures, the limitation of crack width is generally required by building codes to guarantee a minimum service life. Indeed, the presence of wide cracks fosters the damage of steel reinforcing bars due to corrosion and, consequently, compromises the durability of RC elements. To investigate the possible correlation existing between crack width and rebar corrosion, an experimental campaign has been performed on reinforced concrete ties subjected to cyclic actions. More precisely, the same steel bar (having a diameter of 20 mm) has been surrounded by different thickness of plain concrete or fiber reinforced concrete (FRC) cover. In these elements, residual crack widths, measured at the end of the same cycles, are wider in R/FRC than in RC ties. On the contrary, the corrosion of rebar is remarkably lower in R/FRC, especially in the presence of large covers (i.e., in low reinforced ties). Therefore, it seems that the presence of a fiber reinforcement is associated to a lower risk of rebar corrosion, regardless of the crack width.

TC2_B: Parallel Session B: Structural Applications 2

Time: Tuesday, 19/Sept/2023: 2:00pm - 4:00pm · *Location:* Ventura A
Session Chair: Marco di Prisco
Session Chair: Ali Amin

Experimental Study on Steel-Fiber Reinforced Concrete Coupling Beams under Simulated Wind Loading

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The design of structures for wind loading in the United States is typically performed such that the structure remains elastic when subjected to design-level wind loading. In the past few years, however, structural engineers have paid increasing attention to the use of a performance-based wind design methodology, where some degree of inelastic deformations is allowed during extreme wind events. In this study, the behavior of steel fiber-reinforced concrete (SFRC) coupling beams under an extreme wind event was evaluated through reversed cyclic load tests of four large-scale SFRC coupling beams. High-strength, double-hook steel fibers in a volume fraction of either 0.5% or 0.65% were used to simplify beam reinforcement detailing and increase shear strength. The applied loading regime included over 2000 loading cycles, with a dozen inelastic deformation cycles of up to 1.5 times the chord rotation at first yield. Target peak shear stress was either 1.25(f'c)^0.5 or 0.84(f'c)^0.5, MPa, where the specified concrete compressive strength, f'c, was 55 MPa. Steel fibers consisted of 60 mm long and 1 mm diameter double-hooked fibers with a nominal tensile strength of 2275 MPa. All four test beams performed well, with good stiffness retention capacity and only minor concrete spalling and small residual crack widths at the end of the tests. At peak chord rotation, applied shear stress ranged from 0.7(f'c)^0.5 to 1.1(f'c)^0.5, MPa. No yielding of the transverse reinforcement occurred in any of the tests.

Precast Electric Cabins Made With FRC: A Feasibility Study From Mixture Formulation To Structural Design

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The construction sector is one of the most energy-intensive and raw-material demanding human activities and, hence, it contributes a significant share of greenhouse gas emissions. Therefore, making it more sustainable and “greener” is one of the main challenges for policy makers, private

companies and the scientific community. In the last years, several solutions were proposed in the literature and, among them, the use of the spread reinforcement in cement-based composites for the partial replacement of the ordinary steel.

In this context, the present study summarizes the results of an industrial R&D project aimed at evaluating the feasibility of using Fiber Reinforced Concrete mixtures for the production of new precast structural panels for electric cabins. First, some mixtures characterized by a variable amount of steel fibers of different geometric properties are taken in to consideration and investigated in at both their fresh and hardened states. Then, one of those mixture is taken in to account for optimizing the design of the main members of precast electric cabins with the aim to comply with the conde of standards and client specifications. The results show that an adequate mixture proportioning for the concrete production would make it possible to produce at industrial scale FRC panels with steel fibers in partial-to-total replacement of the traditional steel rebars and, at the same time, reducing the thickness of the panels and the overall amount of ordinary steel.

Structural Design, Analysis, and Full-Scale Testing of Ultra-High Performance Concrete Girders

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Ultra-high performance concrete (UHPC) is increasingly being incorporated in the bridge industry. The dense matrix and steel fibers provide superior compressive and tensile strengths and durability. As such, UHPC structural members have the potential for higher strength, ductility, and longevity. Several bridge girder designs have been evaluated based on selected target properties to identify the feasibility and benefit of designing and fabricating UHPC precast, pretensioned girders for bridge superstructures in Texas. Nonproprietary UHPC mixes were designed using locally available materials to achieve these target properties, and three Texas I-shape UHPC pretensioned girder specimens (two Tx34 girders 50 ft long and one Tx54 girder 70 ft long) were designed with conventional cast-in-place concrete decks. The corresponding prototype designs have longer maximum spans and use higher levels of prestressing as compared to standard conventional concrete bridge girders of the same shapes. The experimental program includes four-point bending tests in flexure, along with additional testing of the shear behavior at the girder ends. To study the utilization of the superior tensile strength of UHPC for increasing the shear capacity of the girder, transverse steel reinforcement in one half of the span was eliminated while the minimum web reinforcement for shear was provided in the other half span of the girder specimen. Testing of two Tx34 girders and one Tx54 girder in flexure and shear has been conducted. The results of the load testing of all three girder specimens for service and ultimate demands will be presented.

FRC Double-Layer Thin Slabs Cast into the Asphalt Pavement in a Car Park

Jakob Šušteršič, Aleš Brodnik, Rok Ercegovič, Sandi Drolc

IRMA Institute for Research in Materials and Applications, Slovenia

In this paper, we first give a description of the purpose of casting FRC double thin slabs with a total thickness of 4 to 5 cm into the asphalt pavement of a car park, and then give and discuss the results of preliminary FRC investigations. The slabs will be casted at the locations where individual tires of parked vehicles rest on the pavement (i.e. four locations per parking lot); the slab at the individual location has rectangular floor plan dimensions of approx. 0,75 x 1,35 m. The thickness of the lower layer is 3 to 4 cm and the upper layer 1 cm. The lower layer is made of SFRC with 240 kg of hooked steel fibers with a length of 16 mm and a diameter of 0,5 mm, The effective water-binder ratio is 0,37, limestone aggregate with the largest grain of 4 mm is used. The top layer is made of PFRC with fibrillated polypropylene fibers with a length of 10 mm. The effective water-binder ratio is 0,37, eruptive aggregate with the largest grain of 4 mm is used. We prepared and investigated test specimens from SFRC and PFRC, as well as double-layer test specimens from both FRCs. We investigated the mechanical and durability properties. The obtained results show that SFRC and PFRC are suitable for their intended use.

Improving Flexural Capacity of Ultra-Thin White Topping (UTW) Pavements by Adding Polyvinyl Alcohol (PVA) Discrete Fibers

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Ultrathin white topping (UTW) is becoming an effective rehabilitation technique to extend the service life of distressed asphalt pavement. However, like concrete, UTW is still vulnerable to shrinkage cracking. Discrete fibers have been added to UTW to prevent cracking to improve its flexural capacity. This paper investigates how polyvinyl alcohol (PVA) discrete fibers improve the flexural capacity of the UTW. The concept of effective modulus of rupture determined from the equivalent flexural strength ratio is introduced and used to determine the flexural capacity of UTW. Two phases of the experimental program were carried out. The first phase involves four tests to determine the mechanical properties of concrete layers, including compressive strength, modulus of elasticity, the elastic modulus of rupture, and equivalent residual strength ratio. The second phase involved two different tests in determining the flexural properties of the FRC/asphalt composite specimens, including equivalent residual strength ratio and modulus of rupture. Twenty-two different prisms of concrete beams and FRC/asphalt composite beams included eleven seven cases of different PVA volume content (0, 0.05, 0.1, 0.3, 0.5, 0.8, 1.0, 1.3, 1.5, 1.8, and 2.0%). The results of the first phase showed that using PVA increased the

compressive strength and modulus of rupture of the concrete layer and reduced the modulus of elasticity. In the second phase, the results of the equivalent flexural strength ratio and the effective modulus of rupture of the FRC/asphalt composite specimens significantly improved by adding PVA. Further, the flexural capacity of the composite beam, which was calculated based on the concept of effective modulus of rupture was higher than the capacity of the concrete layer, even for plain concrete.