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Fiber reinforced cement-based composite system for concrete confinement

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ABSTRACT

This paper reports on a feasibility study to develop a reversible and potentially fire-resistant fiber reinforced cement-based matrix (FRC) composite system for concrete confinement applications. The first part of this study aimed at selecting a candidate FRC system from different fiber (including glass and basalt) and inorganic matrix combinations on the basis of: constructability, by verifying the workability and ease of installation on concrete cylinders; structural performance, by evaluating strength and deformability enhancement in confined concrete cylinders tested under uniaxial compression; and compatibility, by examining the quality of the concrete–FRC interface and the level of fiber impregnation using scanning electron microscope images. In the second part of this study, the selected FRC system was further assessed through compression tests of additional concrete cylinders confined using different FRC reinforcement ratios, where both axial and in-plane (radial) deformations were measured to assess confinement effectiveness. The feasibility of making the application reversible was investigated by introducing a bond breaker between the concrete substrate and the composite jacket in a series of confined cylinders. The prototype FRC system produced a substantial increase in strength and deformability with respect to unconfined cylinders. A superior deformability was attained without the use of a bond breaker. The predominant failure mode was loss of compatibility due to fiber–matrix separation, which points to the need of improving fiber impregnation to enable a more efficient use of the constituent materials. Semi-empirical linear and nonlinear models for compressive strength and deformation in FRC-confined concrete are also presented.

1. Introduction

The application of externally bonded fiber reinforced polymer (FRP) systems is a convenient and well established solution to strengthen, repair and retrofit structural concrete members [1]. In particular, confinement of reinforced concrete (RC) columns using FRP systems has become mainstream due to its cost effectiveness and relative ease and speed of application with respect to alternative rehabilitation techniques. Numerous studies have shown that confinement with FRP systems can increase the compressive strength as well as the deformability under vertical and lateral (e.g., seismic) loads [2–5]. This evidence was translated into design guidelines and codes of practice, for example by ACI in the USA [6] and by CSA in Canada [7], respectively. A wide range of organic polymer matrices, typically epoxy-based, are used due to the commercial availability of convenient resin systems that offer adequate compatibility with the reinforcing fibers and the concrete substrate, and durability under aggressive environments, coupled with mechanical (strength, stiffness, toughness) properties that are suitable for structural applications.

Significant margins exist to advance externally bonded composite rehabilitation technologies by addressing the following issues posed by the use of organic polymer matrices. (a) Fire resistance: organic resins are flammable and, unless insulated against fire, degrade under temperatures that are close to or exceed that of glass transition [8], typically ranging from 60 to 82 °C [6]; this process may also be accompanied by the release of toxic fumes, constituting a health hazard. (b) Reversibility: the ability to easily remove and replace a rehabilitation system, impractical for epoxy-based FRP systems, would simplify inspection and integrity assessment after a critical event; in addition, the technology would become more attractive for the conservation of historic structures, where reversibility is desirable [9]. (c) Recyclability: as excess organic resin from a rehabilitation application or from removal is considered a hazardous waste, with limited information being available on recycling or disposal [10], research and development efforts to study more environmentally friendly solutions are consistent with the growing demand for sustainable construction materials and systems. (d) Cost: researching alternatives to reduce the initial cost of externally bonded systems is essential to further the acceptance of this technology [11].

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Nomenclature

D	diameter of plain concrete cylinder
E_f	longitudinal elastic modulus of fiber reinforcement
f_c	average cylinder compressive strength of plain concrete
f_{cc}	compressive strength of confined concrete cylinder
$f_{cc,\mathrm{FRC}}$	average compressive strength of FRC-confined concrete cylinders
$f_{cc,\mathrm{FRP}}$	average compressive strength of FRP-confined concrete cylinders
f_{lu}	confining pressure exerted by FRC jacket at maximum axial stress
f_m	cube compressive strength of hardened inorganic matrix
k_1, m	empirical constants in model of axial strength of confined concrete cylinders
k_2, n	empirical constants in model of axial strain at maximum stress in confined concrete cylinders
n_p	number of plies of fiber reinforcement
t_f	thickness of one ply of fiber reinforcement
ε_c	average ultimate axial strain of plain concrete cylinders
ε_{cc}	axial strain of confined concrete cylinder at maximum axial stress in confined concrete cylinder
$\varepsilon_{cc,\mathrm{FRC}}$	average axial strain at maximum axial stress in FRC-confined concrete cylinder
$\varepsilon_{cc,\mathrm{FRP}}$	average axial strain at maximum axial stress in FRP-confined concrete cylinder
ε_{lu}	hoop strain in FRC reinforcement at maximum axial stress in confined concrete cylinder
ν	Poisson's ratio of concrete
ρ_f	FRC reinforcement ratio
σ_t	splitting tensile strength of hardened inorganic matrix

This paper reports on a feasibility study aimed at devising and evaluating a reversible fiber reinforced cement-based matrix (FRC) composite system for concrete confinement applications, which addresses the issues previously summarized. First, six different combinations of commercially available inorganic binders and reinforcing fibers (including glass and basalt) were experimentally investigated to select a candidate system based on: constructability, where the FRC composites are applied on concrete cylinders to verify the workability of the matrix and ease of installation of the system; structural performance, evaluated at a level suitable for a feasibility study by testing the FRC-confined concrete cylinders under uniaxial compression, together with epoxy-based FRP confined counterparts used as benchmark; and compatibility, where the concrete–FRC interface and the ability of the matrix to penetrate the reinforcing fiber fabrics, both important factors in ensuring efficient stress transfer, are examined via scanning electron microscopy (SEM) analysis. The selected FRC system was further characterized by testing additional concrete cylinders confined using three different external reinforcement ratios, where both axial and in-plane (radial) deformations were measured to assess the confinement effectiveness. Reversibility was addressed by introducing a bond-breaker layer between the concrete substrate and the FRC composite jacket. An analytical model to estimate strength increase and associated axial strain is also evaluated.

1.1. Background

Inorganic binders are of interest as potential matrices in sustainable FRC systems due to compelling properties, including high thermal stability [12], resistance to ultraviolet (UV) radiations and aggressive environments in general, relatively low embodied energy [13], odor and toxic emissions [14] when processed, installed or removed, which minimizes related health and environmental concerns with respect to organic polymer counterparts. In addition, fairly well established practices and processes exist for the safe and correct use of cement-based construction materials, as well as for their disposal and recycling.

Inorganic matrices can have a high degree of chemical and mechanical compatibility with concrete substrates [15]. Their potential for use in structural rehabilitation was first successfully tested on RC beams strengthened in flexure using externally bonded carbon FRC laminates in the late 1990's [16]; comparable performance was attained in terms of flexural strength and post-cracking stiffness increase with respect to RC beams strengthened with carbon fiber sheets bonded using a two-part epoxy resin, with a minor reduction in ductility. It was also observed that inorganic matrices may be characterized by a different load transfer mechanism where local bond slip is accommodated by the formation of several hairline cracks in the matrix that do not propagate, typically resulting in failures due to fiber rupture rather than delamination [17]. Promising results were also obtained in increasing the shear strength of RC beams strengthened with carbon and glass FRP laminates [18,19].

Bond strength and integrity are not as critical in concrete confinement applications, where an intimate contact between the concrete substrate and the composite jacket is the key requisite to engage the rehabilitation system, thereby curtailing concrete dilation. Early attempts showed that comparable increases in axial strength and deformability were attained in concrete cylinders confined using a FRC composite system and a conventional two-part epoxy carbon FRP system [20,21]. A mortar-based composite that used textile carbon fiber reinforcement was developed and tested on confined cylinders and short rectangular columns, showing that jacketing provides a substantial gain in compressive strength and deformability [22], with a comparable confinement effectiveness to an epoxy-based carbon FRP system [23]. Recently, a study proposed the use of basalt reinforcing fiber sheets that were pre-impregnated with epoxy resin, and bonded with a cement-based mortar [24]; increases in compressive strength and axial strain were attained in plain concrete cylinders with respect to benchmark specimens strengthened with an epoxy-based glass FRP jacket.

1.2. Selection of FRC system

The objective of the first part of the feasibility study was to identify a candidate FRC system among different fiber/matrix combinations, on the basis of ease of application, confinement effectiveness with respect to epoxy-based FRP systems with similar fiber reinforcement, and ability to penetrate the reinforcing fibers, and ensure optimal stress transfer. Six fiber/matrix combinations were examined that included different inorganic matrices (water-based and acrylic-based), reinforcing fibers (including glass and basalt), and fiber sheet densities.

1.2.1. Inorganic cement-based matrix

Two different inorganic matrices were investigated: the first based on a commercially available hydraulic cement-based mix formulated to produce a thixotropic matrix with high water retention, herein denoted as "Type H"; and the second based on a