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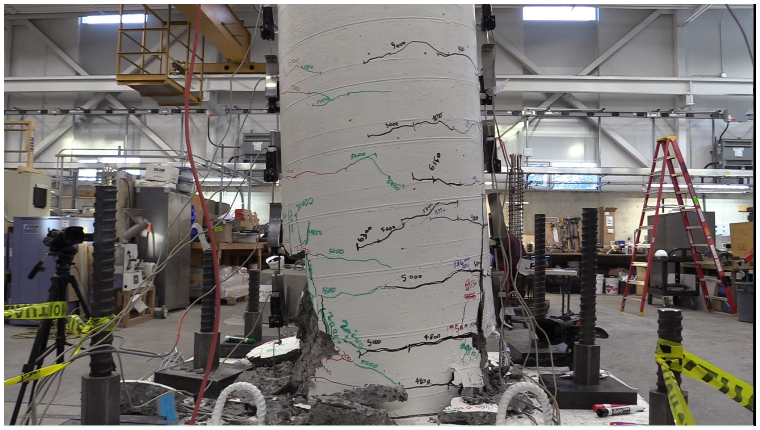

Advances in Repair/Retrofit/Strengthening, Design and Analysis of Structures

SP-358

Editor:
M Shahria Alam

American Concrete Institute
Always advancing

Advances in Repair/Retrofit/ Strengthening, Design and Analysis of Structures

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With the aging and deterioration of infrastructure, the need for repair, strengthening, and rehabilitation of existing structures continues to increase. Climate change makes extending the service life of our infrastructure critical since any demolition and new construction will trigger substantial amounts of carbon emissions. Research related to repairing and strengthening existing infrastructure is seeing major developments as new green materials and technologies become available. Improved assessment and retrofit of deficient structures, and performance-based design of new structures are also in high demand. Despite the progress, there are many challenges yet to be addressed. The main objective of this Special Publication is to present results from recent research studies (experimental/numerical/analytical) on the retrofit and repair of structural elements along with the assessment, analysis, and design of structures. Several of these papers were presented at the ACI Fall Convention "Seismic Repair/Retrofit/Strengthening of Bridges at the Element or System Level: Parts 1 and 2."

The presented studies cover various aspects of structural retrofitting and strengthening techniques including the use of rubberized engineered cementitious composite for enhancing the properties of lightweight concrete elements, high-performance concrete jacketing to strengthen reinforced concrete piers/columns, and the behavior of fiber-reinforced-polymer-wrapped concrete cylinders under different environmental conditions. Additionally, the research explores the behavior of concrete-filled FRP tubes under axial compression, innovative bridge retrofit technologies, and retrofit techniques for deficient reinforced concrete columns. There is also a focus on evaluating the seismic response of retrofitted structures, designing guidelines for seismic retrofitting using tension-hardening fiber-reinforced concrete, strengthening unreinforced masonry walls with ferrocement overlays, and developing seismically resilient concrete piers reinforced with titanium alloy bars. The seismic response of a retrofitted curved bridge was also presented where elastomeric bearings of the as-built bridge were replaced by high damping rubber bearings as a part of the seismic retrofit. Recommendations for nonlinear finite element analysis of reinforced concrete columns under seismic loading are also presented to simulate their behavior up to collapse.

Overall, the presented studies in this Special Publication demonstrate the potential of new materials, methods, and technologies to improve the performance of various structural elements under different loading conditions, including seismic and environmental loads. These studies are expected to help our practitioners and researchers not only develop more effective and sustainable methods for repairing and strengthening of structures but also improve their analysis and design skills.

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Use of Rubberized ECC in repair/strengthening lightweight concrete elements

Basem H. AbdelAleem and Assem A. A. Hassan

Synopsis: This study aims to present a new technology for repairing/strengthening lightweight concrete (LWC) elements. Rubberized engineered cementitious composite (RECC) was used to repair/strengthen LWC specimens to develop a lightweight composite with superior mechanical properties and impact resistance. Two different sizes of rubber aggregate were used in RECC: crumb rubber (CR) and powder rubber (PR). The studied parameters included different RECC layer thicknesses and different cross-section locations. The tested properties were compressive strength, splitting tensile strength, flexural strength, drop weight impact resistance, and flexural impact resistance. The bond strength at the interface between LWC and RECC was also investigated. The results revealed that repair/strengthening LWC with RECC layer showed a promising lightweight composite with enhanced mechanical properties and impact resistance. Using CR in the RECC repair layer showed better enhancement in the drop weight impact resistance than using PR, while using PR was more significant in enhancing the composite's static flexural strength and flexural impact resistance. The results also revealed that the flexural impact resistance of the sample was significantly enhanced when RECC layer was placed on the tension side (bottom side), while the drop-weight impact resistance was noticeably improved when RECC was placed on the compression side (top side).

List of notations

LWC	Lightweight concrete
RECC	Rubberized Engineered cementitious composites
CR	Crumb rubber
PR	Powder Rubber
CRECC	Crumb rubber-Engineered cementitious composites
PRECC	Powder rubber-Engineered cementitious composites
MK	Metakaolin
FA	Fly Ash
C	Cement
BC	Binder content
SCM	Supplementary cementing materials
S	Normal sand
SS	Silica Sand
PVA	Polyvinyl Alcohol fibers
STS	Splitting tensile strength
$f'c$	Compressive strength
B-CRECC	LWC sample with a bottom layer of CRECC
B-PRECC	LWC sample with a bottom layer of PRECC
T-CRECC	LWC sample with a top layer of CRECC
T-PRECC	LWC sample with a top layer of PRECC

Keywords: Rubberized engineered cementitious composites; impact resistance; drop-weight impacts; lightweight concrete; mechanical properties; Crumb rubber; powder rubber; supplementary cementing materials.

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ACI member **Assem A. A. Hassan** is a Full Professor in the Faculty of Engineering and Applied Science at Memorial University of Newfoundland, Canada. His research interests include the development and use of self-consolidating, high-performance, and high-strength concretes; rheology of cement paste and concrete mixtures; durability (porosity, diffusivity, chloride permeability) of concrete structures; corrosion monitoring and accelerated corrosion testing of reinforced concrete structures; service life prediction of concrete structures; and performance of large-scale structural members under loading.

INTRODUCTION

Lightweight concrete (LWC) offers a wide spectrum of architecture and structural benefits, ensuring technical leverage over conventional concrete [1,2]. The low in-place unit weight of LWC clearly reduces the dead load of structural elements and, in turn, reduces the cross-section, steel reinforcement, and total construction cost [3-5]. LWC is also characterized by reduced energy consumption and CO_2 footprint due to the reduction of cement usage in smaller-size LWC elements [6,7]. In addition, LWC has high thermal insulation and fire resistance and reduced handling and transportation cost. Considering the structural performance and strength, LWC was found to provide a more efficient strength-to-weight ratio compared to normal-weight concrete [8-10]. Several structural applications are employing this concrete due to the aforementioned advantages of LWC. For example, post-tension and precast panels, bridge decks, and elevated building decks are frequently made with LWC. Despite the benefits of using LWC in the structural application, the weak and brittle characteristics of lightweight aggregate (LWA) in LWC contribute to reducing the strength of the concrete. Moreover, incorporating LWA in concrete showed to reduce the ductility, energy absorption, and impact resistance of LWC [11-13].

The brittle behavior and low ductility make LWC more susceptible to severe damage under mechanical loading, especially impulsive loading. Such damage can negatively affect the sustainability and integrity of the structure. Therefore, appropriate repair techniques are required to restore the desired strength of damaged LWC elements. Wide range of concrete types were proposed as repair materials for damaged concrete elements. However, in the case of repair LWC, the repair material should be high-performance lightweight concrete to recover the design capacity of the structural elements without affecting the low density of LWC. Engineered cementitious composite (ECC) is considered one of the high-performance concrete composites that can be suitable for repair/strengthening of LWC without causing a significant increase in the self-weight. ECC is a unique class of high-performance cement-based composite that was initially developed in early 1990s based on micromechanics theory. The standard development of ECC includes low-toughness mortar with a polymeric fiber as reinforcement [14]. The low-stiffness mortar is achieved by eliminating the coarse aggregate and only using Portland cement, silica sand, and supplementary cementing materials in developing ECC mixtures [15-16]. ECC proved to have high compressive and tensile strain capacities reached up to 0.65% and 5%, respectively, compared to 0.3% and 0.02%, respectively, of normal concrete [17-20]. The high strain capacity of ECC allows the concrete composite to have high performance under impact and dynamic loading [21]. The absence of coarse aggregate in ECC, which allows the composite to be placed in a thin layer, in addition to the high energy absorption, load carrying capacity, and fatigue life, gave ECC a high potential for repair and retrofitting damaged structural elements.

Incorporating rubber particles in ECC composites can help to further reduce the self-weight and promote the ductility, energy absorption and impact resistance of ECC. The high ductility and low stiffness of rubber aggregate proved to have a significant effect on enhancing concrete ductility, impact resistance, and cracking behavior [22-25]. AbdelAleem et al. [17] investigated the effect of incorporating different percentages of CR in ECC mixtures on the ductility and energy absorption of beam-column joints subjected to cyclic loading. Their investigation indicated that adding up to 15% of CR to the ECC joint enhanced the ductility and energy absorption capacity by 18.3% and 23.2%, respectively, compared to the control ECC joint (without CR). Rubber particles that are commonly mixed in concrete composites can be classified into three sizes, including shredded rubber, crumb rubber (CR), and powder rubber. As the rubber particle size increased, the negative effect on concrete strength increased [26-27]. However, larger rubber particles size, such as shredded rubber, has higher elasticity and damping ratio, which contribute to enhancing concrete