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Retrofitting of damaged reinforced concrete beams with a new green cementitious composites material

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ABSTRACT

Overloading of concrete structures is one of the predominant problems in civil engineering. In extreme cases, this problem may cause structural failure and even collapse. A new green retrofitting material, called Green-USM-Reinforced Concrete (GUSMRC), is currently under development at the Universiti Sains Malaysia. The special characteristics (i.e., high tensile, flexural, and compressive strengths) of GUSMRC make it particularly suitable for retrofitting existing damaged concrete structures. The current study investigates the flexural behavior of damaged concrete beams caused by overloading when retrofitted by precast GUSMRC strips. The results show that the precast GUSMRC strips do not only increase the load carrying capacity by 37% over that of the control beams, but also significantly improve the serviceability of the damaged beams.

1. Introduction

Deterioration is a common problem in concrete structures [1]. This problem is defined as any adverse change in the normal mechanical, physical, and chemical properties on the surface or in the entire concrete structure over time [2,3]. Overloading is considered as one of the most common causes of structural cracks after concrete hardening. In this process, structural cracks only remain active if the overloading condition continues or if settlement occurs [3–7]. In the present study, only overload-related causes of distress in concrete structures are discussed because this process contributes directly to strain induction and leads to crack formation once concrete strain capacity is exceeded [8]. Overloading accelerates structural deterioration under some conditions, which reduces the expected lifetime of a structure [2]. Collapse and failure of structures can occur in extreme cases [9].

Under the present economic climate, rehabilitating damaged concrete structures seem a more viable alternative to demolishing and rebuilding them to meet the more stringent limits on serviceability and the required strength of current codes for carrying high permissible loads [10].

The retrofitting technique that uses ultra-high performance fiber-reinforced cementitious composite (UHPFRCC) bonding system has emerged as an alternative to traditional materials and techniques, such as externally bonded fiber-reinforced plastic (FRP) laminates and steel plates.

Since year 2000, UHPFRCC has been successfully applied in retrofitting or strengthening of reinforced concrete (RC) beams. One of these techniques is the CARDIFRC strip bonding system, which was developed at Cardiff University, United Kingdom. Several studies had been undertaken at Cardiff University into the possibility of using CARDIFRC for the rehabilitation, retrofitting [10–12] and strengthening [13] of damaged RC flexural members.

CARDIFRC is a class of UHPFRCCs characterized by high strength and high cement content (>744 kg/m^3). The key advantage of CARDIFRC mixes for retrofitting is that, unlike steel and FRP, their tensile strength, stiffness, and coefficient of linear thermal expansion are comparable with that of the parent member material. However, their major drawback is the high cement content requirement. Increasing cement content beyond the limit does not enhance the properties of concrete [14,15], but increases the emission of greenhouse gases such as carbon dioxide (CO_2), which contributes to global warming [16,17]. It may also increase electrical energy consumption and the price of concrete [18]. Hence, UHPFRCC products may be considered uneconomical and detrimental to the environment.

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To overcome some of the problems associated with the current techniques, a new class of green UHPFRCCs that contains up to 50% palm oil fuel ash (POFA) is currently being developed at the Universiti Sains Malaysia (USM) by Aldahdooh et al. [19]. This green retrofitting material is known as Green-USM-Reinforced Concrete (GUSMRC). GUSMRC mixtures were designed using two ideal and practical methods: (1) by optimizing the mix design of traditional UHPFRCCs (T-UHPFRCCs) through statistical methods in response to surface methodology (RSM) [20] and (2) by replacing a large portion of the binder of UHPFRCCs optimum mix with a new supplementary cementitious material (UPOFA) [19,21]. The key advantage of GUSMRC mix is that, unlike CARDIFRC mixes, its cement content is less than 360 kg/m^3. This study may lead to a solution for alleviating the environmental and economic effects of cement and POFA.

This research expands on the findings of previous studies without repeating the reported results [19–21]. The optimum GUSMRC mix was applied as a new green retrofitting material to improve the flexural behavior of RC beams damaged by overloading. Moreover, this study aims to examine the flexural behavior of RC beams before and after retrofitting, including crack development, crack modes, flexural capacity, and deflection capacity at different loading levels.

1.1. Research significance

This study aims to investigate the potential of using GUSMRC as a new green retrofitting material. It may expand the utilization of POFA in concrete, reduce cement production, and alleviate the environmental and economic effects of cement and POFA.

2. Materials and methods

In this study, the optimum mix was only used as a new retrofitting material for improving the flexural behavior of damaged RC beams. The materials utilized to produce the optimum mix of GUSMRC and normal concrete (NC) are described in Sections 2.1 and 2.2, respectively. The complete details on the development process of GUSMRC mixtures can be found in previous studies [19–21].

2.1. Materials used for GUSMRC

The constituent materials include ordinary Portland cement ([ASTM], Type 1, 42.5 R); ultrafine POFA with an average particle size of approximately 2.06 μm, 65.01% silicon dioxide, specific gravity of 2.55, and surface area of 1775 m^2/kg; densified silica fume (DSF) with particle size ranging from 0.1 μm to 1 μm, 92% silicon dioxide content, and surface area of 23,700 m^2/kg; mining sand with particle size ranging from 100 μm to 1180 μm and a specific gravity of 2.65; and two short brass-coated micro-steel fibers (6 mm and 13 mm) with a diameter of 0.16 mm and tensile strength of up to 2850 MPa. A polycarboxylic ether-based superplasticizer was utilized to enhance the flow of the mixture [19–21].

The mix proportions and the mechanical properties of the optimum GUSMRC mix are provided in Tables 1 and 2, respectively. The flow of the GUSMRC optimum mix is approximately 171 mm.

Table 2
Mechanical properties of the optimum GUSMRC mix [15,17].

Time	CS (MPa)	DTS (MPa)	FS (MPa)	STS (MPa)	MoE (GPa)
$Avg._7$	150.26	12.40	38.93	–	–
$S.D._7$	3.49	0.17	1.98	–	–
$Avg._{14}$	154.10	–	–	–	–
$S.D._{14}$	2.28	–	–	–	–
$Avg._{28}$	156.72	13.35	42.38	20.46	46.72
$S.D._{28}$	3.32	0.05	0.10	1.20	0.97
$Avg._{90}$	158.28	13.78	46.69	–	–
$S.D._{90}$	2.68	0.48	5.25	–	–

CS = Compressive strength; DTS = Direct tensile strength; FS = Flexural strength; STS = Splitting tensile strength; MoE = Modulus of elasticity.
$Avg._7$, $Avg._{14}$, $Avg._{28}$ and $Avg._{90}$ refer to the average of strength values at 7, 14 28 and 90 days respectively.
$S.D._7$, $S.D._{14}$ and $S.D._{28}$ refer to the standard deviations of strength values at 7, 14 and 28 days respectively.

2.2. Materials used for RC beams

In this study, 24 RC beams with a span length of 1100 mm were prepared according to the study of Alaee and Karihaloo [10]. The reinforcement details and mix proportions of the NC are presented in Fig. 1 and Table 3, respectively. Based on the slump test results, the average values of slump varied between 150 mm and 180 mm ASTM: C143/C143M [22].

2.3. Test methods

As mentioned earlier, the optimum GUSMRC mix was used as a retrofitting material in this study to enhance the flexural behavior of RC beams damaged by overloading. As shown in Fig. 2, GUSMRC was cast as strips in special molds and used as externally bonded strips for retrofitting according to the procedure presented by Alaee and Karihaloo [10]. GUSMRC strips were bonded to designated places on the damaged beam surfaces using CONCRESIVE®1441S epoxy adhesive. The complete steps are detailed in Alaee and Karihaloo [10]. Table 4, shows the summary of the mechanical properties of normal concrete at 28 days.

A total of 27 RC beams (Fig. 1) were prepared in this study. These beams were divided into three groups [G (0), G (I), G (II)] for testing. All beams were tested in a four-point loading under cyclic loading to examine flexural behavior (Fig. 3). Table 5 shows the notations for all beams in each group. The four-point load test was performed using a structural testing frame. The test setup consisted of a load cell (Model 1232AF- 100K-B) with a maximum capacity of 500 kN, a series of three linear variable displacement transducers (LVDTs) that were mounted to measure vertical displacements (Fig. 4), and a Kyowa data logger (Model UCAM-20PC) that was used to record all measurements received from the load cell and the LVDTs.

The beams in the first group [G (0)/three trial beams (TB)] were tested in four-point loading under cyclic loading until failure (P_u) occurred to indicate the load/damage level (%P_u). The first visible cracks, distribution of flexural cracks, start of shear crack propagation, crack localization, and beam failure were also tested. The beams in the second group [G (I)/six controlled beams (CB)] were bent to examine flexural behavior, including crack development,

Table 1
Optimum GUSMRC mix proportion [15,17].

	OPC	DSF	UPOFA	M.S.	W	SP	SF		W/B	SP/B
							l_1	l_2		
Composition (kg/m^3)	360.25	214.25	290.52	1057.3	168.3	50.43	390	78	0.195	0.058

OPC = Ordinary Portland Cement; DSF = Densified Silica Fume; SF = Steel Fiber; UOPFA = Ultrafine Palm Oil Fuel Ash; SP = Superplasticizer; W = Water; B = Binder; M.S. = Mining sand; l_1, l_2 = Two short brass-coated micro-steel fibers lengths.