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A novel corrosion resistant repair technique for existing reinforced concrete (RC) elements using polyvinyl alcohol fibre reinforced geopolymer concrete (PVAFRGC)

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HIGHLIGHTS

- Fibre reinforced geopolymer concrete (FRGC) can offer improved corrosion resistance.
- Application of FRGC can improve the structural performance of existing elements.
- Good interface conditions between FRGC and normal concrete can be achieved.

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ABSTRACT

Strain hardening fibre reinforced geopolymer concrete, which utilises waste material rather than primary mineral products and is suitable for cast-in-place applications, shows considerable potential as a resistant, more environmentally friendly, concrete repair material. This study assesses the corrosion protection performance of polyvinyl alcohol fibre reinforced geopolymer concrete as a repair material. The applicability of polyvinyl alcohol fibre reinforced geopolymer concrete as a repair material for preventing steel corrosion was investigated using specimens that simulated surface coating repair. Large scale beam repair was conducted using beams where part of the concrete cover at various depths (12.5% and 25% of the total beam depth) was replaced by polyvinyl alcohol fibre reinforced geopolymer concrete. Accelerated corrosion tests were performed using an induced current technique by applying a nominal 300 mA/cm^2 constant anodic current for approximately 90 days. Results from flexural strength tests showed significant improvements in the structural performance of the reinforced concrete beams repaired with polyvinyl alcohol fibre reinforced geopolymer concrete following accelerated corrosion. The results can be summarised as follows: surface coating with polyvinyl alcohol fibre reinforced geopolymer concrete significantly reduced corrosion damage in terms of mass loss, crack distributions and structural performance, while differences in surface coating thickness also considerably affected the corrosion resistance of the repaired beams.

1. Introduction

Reinforced concrete (RC) structures in marine and coastal areas are continuously exposed to a chloride-rich environment, which leads to deterioration of the concrete and its reinforcement bars [1–3]. Corrosion of steel reinforcement bars causes a reduction in their cross-sectional area, and produces corrosion products with a higher volume than the original steel leading to cracking of the concrete cover. The cracking also increases the corrosion rate, and decreases the bond effectiveness between steel bars and concrete, leading to a reduction in load carrying capacity and the safety performance of the concrete structure [4,5]. In recent years, RC structure deterioration has motivated the development of innovative and new materials and techniques for structural repair, as replacement of existing structures would be very costly, and in most cases prohibitively expensive [1]. In this study an induced current testing technique was employed to accelerate corrosion

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over a relatively short period (i.e. 90 days) in order to make comparisons between specimens with a significant degree of corrosion. This technique has been widely used in previous studies, which have proven that the induced current method can accurately simulate the effect of corrosion over short (experimental) periods [6–8].

A range of research studies have focused on the repair of existing structures. Most of this research uses a traditional patch repair method which applies polymer cement mortar (PCM) to repair concrete structures, or uses repair techniques based on externally bonded steel plates, reinforced concrete jacketing [9,10], or use of externally bonded Fibre Reinforced Polymer (FRP). While all of these methods and materials have been used relatively successfully for the rehabilitation of reinforced concrete structures and are yielding excellent results for some specific applications, there is still a need to develop a material capable of extending structure service life in severe environmental conditions with a minimum of maintenance. In particular, the use of externally glued FRPs as well as steel plates can have issues around fire resistance. The use of reinforced concrete jacketing systems needs to apply concrete layers with thicknesses larger than 60–70 mm as the presence of reinforcing bar requires a minimum concrete cover [11]. Moreover, these repair techniques cannot protect repaired concrete structures damaged by chloride attack from re-deterioration processes, due to physical and electrochemical incompatibilities between the repair material and substrate concrete [12].

Fibre reinforced cementitious composites (FRCC) are materials composed of a cement-based matrix with short discontinuous fibres. Generally, the addition of fibres to a concrete mix considerably enhances many of the mechanical properties of concrete such as flexural, impact, tensile, and abrasion strength, cracking distribution and post cracking behaviour [13,14]. While numerous cracks can be generated under tensile stress following fibre addition, these cracks have low permeability to chloride, oxygen and moisture ingress since crack width is very small. While steel fibres are the most commonly used type of fibre, Polyvinyl Alcohol (PVA) fibres have also been successfully used for the enhancement of the mechanical properties of conventional concrete in previous studies [15–18]. Li et al. (2001) [18] studied the strain hardening performance of fibre reinforced mortar containing 2% PVA fibre with a surface oil coating. The strong chemical bond between the cementitious matrix and the oiled PVA fibres led to the rupture of bridging fibres rather than their pull-out during the opening of a matrix crack. Therefore, a fibre surface oiling was applied to weaken the bond and provide 'pseudo' strain hardening characteristics. Lee et al. (2012) [19] examined the strain-hardening behaviour of a PVA fibre reinforced cement-less mortar with Alkali Activated Slag (AAS). Test results showed a significant improvement in tensile strain values, which reached up to 4.7% (and which were considerably higher compared to the respective values for the unreinforced matrix, which were around 0.02%).

Regarding cost, the PVA fibres have similar cost per weight compared to steel fibres. However, the quantity of PVA fibre used is six times less than steel fibre at the same volume fraction, therefore the cost of PVA fibre reinforced concrete mixture is considerably lower compared to the cost of the respective material reinforced with steel fibres. Moreover, in the current study the cost of the geopolymer matrix material is further reduced by lowering the potassium silicate content and avoiding heat curing treatment [14].

These fibre-rich materials therefore show potential as a more resilient repair and strengthening material, particularly under chemically aggressive environmental conditions. Recently, novel techniques using fibre reinforced concrete (FRC) layers or jackets have been proposed to improve the performance of existing structural members [11,20–22]. Simultaneously, fibre reinforced geopolymer concretes (FRGC) have emerged as novel engineering materials with the potential to form a substantial element of an environmentally sustainable construction and building products industry [23]. Fibre reinforced geopolymer composites with higher ductility and strain hardening behaviour have been developed in our previous work [14,23]. Based on the earlier phases of the material development, polyvinyl alcohol fibre reinforced geopolymer concrete (PVAFRGC) materials showed superior durability characteristics in term of resistance to sulphuric acid attack, corrosion resistance and chloride penetration which is in agreement with previous studies on the durability properties of geopolymer mortar and geopolymer concrete [24–26]. The FRGC matrix composition is similar to that of normal mortar and concrete, therefore FRGC materials are expected to be highly applicable as surface coating or patch repair materials for the repair and preventive maintenance of reinforced concrete structures that have already deteriorated, or that will deteriorate due to steel corrosion. However, research on FRGC has mainly focused on its mechanical performance, such as its tensile strength and post cracking behaviour and, to date, there are no published studies on the evaluation of the structural performance of FRGC, and its applicability for repair of and preventive maintenance against steel corrosion, in comparison to untreated reinforced concrete beams. Recently, the usage of geopolymer matrix as a repairing layer or as a binding agent to ensure the adhesion between fibre reinforced sheets/ strips and the concrete substrate has been investigated with favourable results [27,28]. However, there are not any published studies to date on the use of unreinforced geopolymer mortars for repair applications since the high shrinkage strain values may lead to de-bonding of the new mortar. Also, there are no published studies to date on the durability performance of RC elements strengthened or repaired with geopolymer concrete.

Electrochemical incompatibilities of RC and repair mortar affect the initiation of macrocell corrosion between the repair material and the substrate. Electrochemical compatibilities are attributed to the electrochemical potential imbalance when the two materials (i.e. repair material and substrate) contact due to the variations of the physical and chemical properties of the two materials [29]. The electrochemical incompatibilities of RC and PVAFRGC have not been examined in the current study, and this could be part of a future investigation in this field.

The main aim of this study was to investigate the corrosion protection performance of FRGC (specifically PVAFRGC) used as repair material of varying thickness (12.5% and 25% of the total RC beam depth). Two different depths of the repair layer were examined in order to evaluate the effect of the thickness of the repair layer on the durability and on the structural performance of the elements. These two values were selected as two characteristic cases of repair techniques by simply replacing the concrete cover (12.5% of the total RC beam depth) or by also replacing existing concrete around the reinforcement bars (25% of the total RC beam depth).

For comparison, monolithic RC beams made entirely using normal (conventional) concrete with a cross section of 100×200 mm were used as controls. Accelerated corrosion studies were undertaken using an induced current technique by applying a nominal 300 mA/cm^2 constant anodic current for 90 days. The effect of accelerated corrosion on the mass loss of the steel reinforcements, failure mode, crack distribution, load carrying capacity and interface slip measurement between the substrate and the repair layer, was examined.

2. Experimental program

2.1. Materials, mixture proportions and mechanical properties

Geopolymer concretes can be synthesized by mixing an alkaline solution with industrial aluminosilicate waste materials, and their adoption could considerably reduce the carbon dioxide emissions associated with the manufacturing of conventional Portland cement. However, based on previous studies [30–32], fly