Construction and Building Materials 152 (2017) 285–303

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Effect of acid attack on FRP-to-concrete bonded interfaces

S.A. Hadigheh [a], R.J. Gravina [b,*], S.T. Smith [c]

[a] School of Civil Engineering, The University of Sydney, NSW 2006, Australia
[b] School of Engineering, RMIT University, Melbourne, VIC 3000, Australia
[c] School of Environment, Science and Engineering, Southern Cross University, Lismore, NSW 2480, Australia

ARTICLE INFO

Article history:
Received 4 January 2017
Received in revised form 6 June 2017
Accepted 21 June 2017

Keywords:
Durability
FRP
Concrete
Acid
Interface
Resin
Environmental effect
Accelerated test method

ABSTRACT

Due to a wide range of fibre reinforced polymer (FRP) material applications in structural strengthening, the long-term performance of FRP-to-concrete bonded interfaces has become an important area of research. Aggressive environmental factors such as temperature variation, wet/dry cycles, sulphate attack, acid attack, or UV radiation may noticeably change the service life of an FRP-strengthened reinforced concrete (RC) structure. Amongst the possible external aggressive conditions, acid impact on FRP-strengthened structures has received limited research attention in comparison to other environmental conditions. Industrial growth and climate changes within the last century has increased the exposure of structures to acidic environments arising from acidic rainfalls, acidic soils, sewage systems, mining, agriculture, and power stations. This paper provides an overview of the impact of acidic conditions on FRP-to-concrete bonded interfaces. Such interfaces are of central importance to the success of FRP strengthening measures for concrete structures. The individual components of concrete, resin matrix, fibre, and the interface between the FRP and the concrete are investigated. Potential degradation mechanisms are discussed, as well as experimental methodologies and research needs.

1. Introduction

It has been more than two decades since the application of FRP composites has attracted the attention of civil engineers for construction of new structures or the rehabilitation of existing structural elements [1]. FRP composites have been used in the civil engineering industry since the late 1980s [2–4]. Since then, a variety of strengthening strategies have been proposed for reinforced concrete (RC) structural elements such as beams [5–11], columns [12–16], joints [17–22], walls [23–27] and slabs [28–32].

Harsh environments, such as high and variable humidity, temperature, chloride, sulphate, and/or acidic conditions can undermine the structural integrity of FRP-strengthened concrete structures, and can significantly impact upon the behaviour and failure mechanism of the FRP-to-concrete bonded interface. While in recent years there has been some research conducted into the effect of harsh environmental conditions on FRP strengthened concrete structures, very limited research has been conducted on the impact of acidic environments on such systems. Although FRP material is highly durable against corrosion and acid attack, the effects of acid on the interface is not widely investigated [33].

Treatment, rehabilitation, and strengthening of the built environment can incur economic costs for infrastructure authorities in regions of acid contamination. The socioeconomic losses associated with infrastructure deterioration due to acid attack exceed billions of dollars all around the world. Reports indicate that in 1993, acid rain caused US$5 billion worth of damage annually in just 17 states of the USA [34]. In addition, acid sulphate soils are spread throughout coastal regions in Australia, which are home to the majority of the Australian population and industries. It is estimated that the cost of treatment and rehabilitation of infrastructure exposed to acid sulphate soil in just the state of Queensland alone is approximately AU$189 million per year [35]. In the UK, the cost of damage to buildings from acid rain was reported to be over US$28.8 billion in 1995 [36]. In 2003, acid rain caused annual economic losses of $13.3 billion which is about three per cent of China's gross domestic product [37].

Since concrete is a highly alkaline material (pH > 12), acids can deteriorate FRP-strengthened concrete structures in various ways. The production of sulphuric acid can result from the combination of moisture and combusted sulphurous gases in fuels, peat soils, clay soils, as well as oxidation of sulphide minerals (pyrite and marcasite) in groundwater, alum shale after oxidation of iron sul-

* Corresponding author.
E-mail addresses: ali.hadigheh@sydney.edu.au (S.A. Hadigheh), rebecca.gravina@rmit.edu.au (R.J. Gravina), scott.smith@scu.edu.au (S.T. Smith).

http://dx.doi.org/10.1016/j.conbuildmat.2017.06.140
0950-0618/

Table 1
Exposure of structures to different acids.

Acid Type	Chemical Formula	Exposure of Structures to Acids
Acetic acid [41]	$C_2H_4O_2$	Can attack agricultural structures due to presence in silage effluents. It exists in food and agricultural products (e.g. cider, household vinegar), food processing plants, paper mills, silos, or garbage feeding floors for hogs. Also produced in animal houses due to the decomposition of meal or agricultural products.
Boric acid [42]	H_3BO_3	Can affect structures near to seawater, volcanic districts, and agricultural products.
Carbolic acid [43]	C_6H_6O	Produced from petroleum or exists in coal tar.
Carbonic acid [44]	H_2CO_3	Attacks buried concrete structures due to acidic ground water or dissolution of carbon dioxide in water.
Formic acid [45]	CH_2O_2	Can be produced in animal houses due to decomposition of meal or agricultural products.
Humic acid [43,46]	$C_{187}H_{186}O_{89}N_9S_1$	Used in soil supplement in agriculture. It can attack marine structures due to existence in ocean water
Hydrochloric acid [41,47]	HCl	Exists in house cleaning solutions, leather processing, and oil productions
Lactic acid [41]	$C_3H_6O_3$	Can attack agricultural structures due to the presence in silage effluents, food and agricultural products (e.g. milk, yogurt, cheese or beer). It is used in the detergent industry.
Nitric acid [48]	HNO_3	Used in fertilizers and can be seen in acidic rain or mist
Oleic acid [49]	$C_{18}H_{34}O_2$	Exists in food products (e.g. oils and fats)
Sulphurous acid [50]	H_2SO_3	Can attack structures exposed to waste water from coal mines.
Phosphoric acid [48]	H_3PO_4	Exists in food products, fertilizer feedstock, and home cleaning products.
Sulphuric acid [41,51]	H_2SO_4	Exists in acidic rain or mist, lead-acid batteries, fertilizers, or sewage systems. It is used in water treatment, and oil refining. Pyrite in acid sulphate soils oxides with exposure to air and produces sulphuric acid. Structures exposed to waste water from coal mines, or buried concrete structures (due to ground water or dumping chemicals from industrial process) can be attacked by sulphuric acid
Tannic acid [45]	$C_{76}H_{52}O_{46}$	Exists in food products (e.g. beer, soft drinks, and juices)

phide (pyrite), and bioactivities of the anaerobic bacteria in sewage systems. Acids may also be found in rainfall, sewage, leachates, animal houses/farms due to decomposition of meal/agricultural products, and industrial water [38–40]. Mineral water may contain dissolved carbon dioxide or hydrogen sulphide. Large quantities of effluents are produced in agricultural and food industries which cannot be released into the environment without treatment. The treatment usually involves concrete facilities to house the waste. These effluents may react with other chemicals and are transformed to substances such as acetic, lactic, oxalic or citric acids which can deteriorate the structure.

Table 1 summarises the possible exposure scenarios of structures in acidic environments.

This review paper considers a wide variety of issues associated with acid attack on FRP-strengthened concrete structures. Since damage may be inflicted to the FRP material, to the resin, or to the concrete substrate, this paper focuses on the impact of an acidic environment on the separate elements of the strengthening system (e.g. concrete, resin matrix, fibre) as well as the interface layer. Initially, the effect of acids on structures and associated guidelines are presented. Then, the effect of acid on FRP-concrete bonds is presented. Finally, existing experimental methodologies and set-ups are presented as well as research recommendations.

2. Acid attack on structures

Deterioration of adhesively bonded members is a synergistic action. That is, when a structure is exposed to aggressive environments, deterioration takes place not only by one isolated factor, but several causes may affect durability of the joint simultaneously. Therefore when durability is a matter of concern, it is essential to determine the most realistic chemical composition which can simulate the realistic condition of the structure. For this reason, codes of practice as well as standards consider the most effective elements. In addition, care must be taken in interpreting the

Table 2
Various standard testing methods to study acid/sulphate attack.

Interface Element	Conditioning Method	Description	Code
Concrete	Acid	Guide To The Use Of Waterproofing, Dampproofing, Protective, And Decorative Barrier Systems For Concrete [52]	ACI 515
		Guide to Durable Concrete [38]	ACI 201.2R
	Sulphate attack	Standard Test Method for Length Change of Hydraulic-Cement Mortars Exposed to a Sulphate Solution [53]	ASTM C1012
		Standard Test Method for Potential Expansion of Portland-Cement Mortars Exposed to Sulphate [54]	ASTM C452
		Building Code Requirements for Structural Concrete and Commentary [55]	ACI 318
		Guide to Durable Concrete [38]	ACI 201.2R
	Chemicals	Standard test methods for chemical resistance of mortars, grouts, and monolithic surfacings and polymer concretes [56]	ASTM C267 – 01
Adhesive	Chemicals	Standard Practice for Resistance of Adhesive Bonds to Chemical Reagents [57]	ASTM D896 - 04
		Test Method for Effect of Bacterial Contamination on Performance of Adhesive Preparations and Adhesives Films (Withdrawn 1990) [58]	ASTM D4299-83
		Standard Practice for Determining Chemical Resistance of Thermosetting Resins Used in Glass-Fiber-Reinforced Structures Intended for Liquid Service [59]	ASTM C581-03
Coatings	Acid attack	Standard Test Method for Gross Defects and Mechanical Damage in Metallic Coatings by the Phosphomolybdic Acid (PMA) Method [60]	ASTM B877
		Standard Test Method for Acid and Mortar Resistance of Factory-Applied Clear Coatings on Extruded Aluminum Products [61]	ASTM D3260