Construction and Building Materials 84 (2015) 192–200

Contents lists available at ScienceDirect

Construction and Building Materials

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

Developing a polymer-based crack repairing material using interpenetrate polymer network (IPN) technology

Hao Wu [a,b,*], Meijia Zhu [a], Zhuo Liu [a], Jian Yin [c]

[a] School of Civil Engineering, Central South University, 22 South Shaoshan Rd., Changsha, Hunan 410075, PR China
[b] National Engineering Laboratory for High Speed Railway Construction, Central South University, 22 South Shaoshan Rd., Changsha, Hunan 410075, PR China
[c] School of Civil Engineering & Mechanics, Central South University of Forestry and Technology, 498 South Shaoshan Rd., Changsha, Hunan 410004, PR China

HIGHLIGHTS

- We develop a repairing material for concrete cracks using IPN technology.
- The material can inherit and integrate desired properties from its components.
- The material's properties are adjustable to accommodate different requirements.
- The material has great potential for crack repair of various concrete structures.

ARTICLE INFO

Article history:
Received 27 December 2014
Received in revised form 5 March 2015
Accepted 8 March 2015
Available online 21 March 2015

Keywords:
Crack repairing
Epoxy acrylate
Methyl methacrylate
Polyurethane prepolymer
Interpenetrate polymer network

ABSTRACT

Crack repairing is considered a cost-effective method in the repair and rehabilitation work for concrete, provided that right repairing materials are selected and properly applied. This paper proposes a polymer-based crack repairing material named EMP by synthesizing epoxy acrylate (EA), methyl methacrylate (MMA), and polyurethane (PU) prepolymer utilizing interpenetrate polymer network (IPN) technology. The physical and mechanical properties of EMP were evaluated through a series of experiments, and the bonding behavior of the material for the crack repairing of concrete structure was also evaluated with composite specimens. The findings from the study demonstrate the repairing material has great potential for repairing concrete cracks with desirable operability, adhesive strength and cracking resistance, and its properties could be adjusted within a certain range through various mix proportions to accommodate different requirements for applications.

1. Introduction

Deterioration of concrete in majority of structures is manifested by cracking [1,2]. Cracks in structures may occur due to excessive loads, thermal stress, shrinkage, corrosion of reinforcement, and differential settlement of support [3–6]. When a crack is observed on the surface of the structure, it is a sign of reduction in its integrity, and under the combined actions of external and internal stresses as well as environmental media, failure to repair cracks may lead to accelerated deterioration of the structure in the forms of crack growth, secondary cracks, and even fractures [3,7–9].

There are many approaches available for retrofitting and strengthening damaged concrete structural elements, in which crack repairing is always considered a cost-effective one, provided that right repairing materials are selected and properly applied [2,10,11]. Crack repairing is essential for a deteriorated concrete structure not only because it can improve its function and performance, restore its structural integrity, but guarantee its durability by preventing ingress of moisture, oxygen, chloride, and carbon dioxide etc. [4,12,13].

Currently, numerous materials have been developed for the repairing of concrete cracks, which range in their compositions from polymer-based adhesives or healing agents [14–18], cementitious grouting materials [19–22], bituminous binder and sealant [23,24], electrolyte solutions [25–27] to more recently developed bio-based agents [28,29]. However, due to the complexity of concrete cracks and the existing discrepancies in compatibility between the repairing material and concrete substrates, re-openings of the structure after being repaired are still inevitable [10,30,31].

Among the diversity of crack repairing efforts, using polymer-based materials either by injection, grouting or gravity pouring

* Corresponding author at: School of Civil Engineering, Central South University, 22 South Shaoshan Rd., Changsha, Hunan 410075, PR China. Tel.: +86 18073158227.
E-mail address: haoutk@csu.edu.cn (H. Wu).

http://dx.doi.org/10.1016/j.conbuildmat.2015.03.067
0950-0618/

to fill and bond the crack are the most common ways [32–34]. Epoxy resin contains a series of particular active and polar groups, such as epoxide, hydroxy and ether bond, which endow epoxy-based materials with high stiffness and strength, excellent adhesive properties and abrasion resistance. However, due to the high crosslink density and internal stress generated during solidification reactions, solidified epoxy-based products usually exhibit high brittleness, poor impacting, bending and cracking resistances, which becomes the crucial reason impairs the compatibility of the repairing system [10,30]. It is well-known that most of the durability problems of repairing system are due to the lacks of compatibility with the concrete substrate, and secondary failure is usually resulted from a combination of physical, chemical and mechanical actions [30,31]. According to the fact that the requirements for crack repairing always vary with applications, modifications should somehow be made to remedy those defects of epoxy-based materials to meet them.

2. Objective and scope

The objective of this study was to introduce a newly-developed polymer-based material for the crack repairing of concrete structures. Interpenetrate polymer network (IPN) technology was adopted to synthesize the repairing material with three widely used polymers. The preparation principles were discussed and a series of experiments were carried out in the laboratory to evaluate the physical and mechanical performances of the repairing material. In addition, SEM analysis was also performed to understand the characteristics of the material from microscopic perspectives.

3. Materials

3.1. IPN technology for EMP material

IPN is a combination of at least two polymers exhibiting different characteristics. A composite material with IPN structure is prepared when one polymer network is synthesized or cross-linked independently in the presence of another polymer without any covalent bonds between them. IPNs can produce synergistic effects by sharing the properties of all polymers consequently avoiding the limitations of natural as well as synthetic polymers, and they are often created for the purpose of conferring key attributes of one of the components while maintaining the critical attributes of the others [35,36].

In the study, the IPN technology was adopted for synthesizing the repairing material named EMP using three widely used polymers: epoxy acrylate (EA), methyl methacrylate (MMA), and polyurethane (PU) prepolymer. Regarding those three components, EA is the production of esterification reaction from open-looped epoxy resin and unsaturated monobasic acid (e.g. acrylic acid), which combines the excellent physical and chemical properties of epoxy resin, as well as the processability of unsaturated polyester. However, similar to epoxy resin, solidified epoxy acrylate resin features high brittleness, poor impacting, cracking and aging resistances; MMA is an active diluents used to reduce the viscosity of the pure EA to improve the operability, flowability and penetrability of the mixture; while PU is a resilient, flexible and durable manufactured material that can improve the ductility and flexibility of the repairing material to some extent, and thus enhance the compatibility between the repairing material and concrete substrates.

In addition to those polymers, evocating, accelerating and cross-linking agents are required to arouse and motivate the interpenetrating reactions of the mixtures to form uniform and stable IPN structures.

3.2. Mixture design

The determination of appropriate recipes for a repairing material is a function of the types of targeted structure, existing stress and environmental exposure conditions, and the time constrains placed on the repairing constructions. In addition, the material should be designed based on achieving certain minimum strengths in a short duration, so that the structure can be put into immediate service.

The mixture designs for the EMP material are presented in Table 1. Assuming the content of EA is 100%, the contents of the other components in the mixture are all calculated based on that. The proportions of MMA are mainly dependent on the expected viscosity of the repairing material as required by applications, and the more the MMA used the lower viscosity the mixture solution can obtain. PU is added in the mixture to endow the solidified material with excellent bending, impacting and cracking resistances, but it could reduces the flowability of the mixture and the strength of the solidified material to some extent, thus the proportions of PU are determined by the required mechanical characteristics for the material. The amounts of the special agents generally have insignificant influence on the performances of EMP material, but they are determining factors for the reaction speed and the uniformity of reaction products. The proportions of those agents are determined by considering the field temperature and required time for implementation.

3.3. Material preparation principles

During the preparation process, the EA was first diluted with a certain amount of MMA to achieve expected operability for the mixture solution. When the mixture reaches a uniform viscosity, it is then thoroughly mixed with PU (the PU added in the mixture could change the viscosity slightly). After that, the evocating agent, accelerating agent and cross-linking agent are added into the mixture orderly. Uniformity is essential for the characteristics of the repairing material, to achieve that, mixing efforts with 5 min. mixing time using mechanical mixer are required for the whole preparation process. The uniformity of the mixture solution could be confirmed with the uniform color it appears. With different contents of PU, the ready-mixed material usually presents different colors during and after solidification. The higher content of PU, the darker the color of the material, as shown in Fig. 1.

The primary mechanisms and principles for the reactions to synthesize EMP can be summarized as follows:

(1) The curing reaction between the active dilution agent MMA and EA is a free radical polymerization. There are three possible reactions during this process: self-polymerizations of both MMA and EA, in which homopolymers are generated; and the copolymerization between MMA and EA, in which macromolecular network structures are generated. The free-radical polymerization reactions normally include three stages: chain initiation, chain growth and chain termination, and might be accompanied with chain transfer reactions.

Fig. 1. EMP mixtures with different contents of PU (left: 10%, right: 50%).

Table 1
Mixture design for the EMP material.

Item	Component	Chemical name	Content	Proportion[a] (ratio by weight)
A	EA	Epoxy acrylate	100%	
B	MMA	Methyl methacrylate	30–70%	MMA:EA = 0.3–0.7
C	PU prepolymer	Polyurethane prepolymer	10–50%	PU:EA = 0.1–0.5
D	Evocating agent	Benzoyl peroxide dimethyl phthalate	1.0–3.0%	1.0–3.0% of EA
E	Accelerating agent	N,N-dimethylaniline styrene solution	1.0–3.0%	1.0–3.0% of EA
F	Cross-linking agent	1,4-Butanediol dehydration	0.2–1.0%	2.0% of PU

[a] The proportions of evocating and accelerating agents are dependent on the content of EA, while the proportion of the cross-linking agent is dependent on the content of PU.