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Strengthening of concrete beams by monolayer prepreg composites with and without graphene reinforcement

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HIGHLIGHTS

- To understand monolayer (MP) and graphene-reinforced monolayer prepreg (GMP).
- To evaluate the structural contribution of MP and GMP.
- To investigate the influence of graphene on the mechanical characterizations of MP.
- To understand effectiveness of MP and GMP applied to plain concrete (PC) beams.
- To prove a reliable approach for strengthening and retrofit of concrete structures.

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ABSTRACT

Composite materials are widely used in different engineering fields and they are very efficient for engineering applications. Several composite materials are in use along with the technological innovations in materials and construction techniques. This study focuses on the monolayer prepreg (MP) composites and graphene-reinforced monolayer prepreg (GMP) composites and their structural contribution to the structural performance of concrete beams. The main objectives of the study are (1) to understand the mechanical properties of the MP and GMP composites, (2) to investigate the influence of graphene on the mechanical characterizations of the MP composites and (3) to compare the strengthening effectiveness and configurations of the MP and GMP composites applied to plain concrete (PC) beams. For this purpose, the MP and GMP composites are produced as continuous sheets and concrete beams are strengthened with these sheets considering four different internal and external strengthening configurations. The flexural behavior of the PC beams is compared to reinforced beams with MP and GMP composites through experiments, numerical simulations and statistical tests. The results indicate that the tensile strength of the MP composite increases by addition of graphene leading to more effective strengthening by the GMP composites, especially with external configuration, than the MP composites.

1. Introduction

Concrete is a stone-like brittle material with high compressive strength and low tensile strength. Thus, cracks and possibly failure of concrete structures occur due to tensile stresses exceeding the corresponding low strength. Hence, engineers have made several efforts to utilize the high strength concrete materials in compression in conjunction with strengthening materials to minimize the effect of the tension forces. Today, concrete materials are generally reinforced with steel bars. However, steel bars are heavy construction materials and the increased mass increases the forces (self-weight and/or inertia forces) on the structures. Therefore, the total amount of steel materials has been reduced by using various optimization methods [1–4] or the use of alternative materials to steel materials is emphasized [5,6]. Recently, strengthening of concrete structures with different engineering materials has gained the interest of many researchers to develop and study new strengthen-

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ing materials [7–10]. At this point, using composite materials has gained attention from the engineering community since they provide effective and economical design or retrofitting solutions for structures ranging from small to large sizes [11–23]. According to the American Concrete Institute (ACI), composite materials might be an alternative to steel plate bonding, section enlargement, and external post-tensioning for strengthening concrete structures [24]. Moreover, many standards developed in different countries focus on the use of composite structures in the construction industry and their structural design and application process [24–32].

In recent years, there have been several efforts to increase the ultimate load-carrying capacity and improve the structural behavior of structures with composite materials [33–38]. In previous research, fiber reinforced polymer (FRP), glass FRP (GFRP), carbon FRP (CFRP) or monolayer prepreg (MP) composites were used as strengthening materials [38–42]. Moreover, nano-technological advances have brought in nano-particle reinforced composite materials and encouraged the use of new composite materials such as graphene-reinforced MP (GMP) and hybrid carbon nanotube reinforced CFRP (CNT-CFRP) composites as strengthening materials [43–47]. However, the literature still lacks comprehensive studies on the effects of the MP and GMP composites on the structural behavior of concrete structures. Therefore, this study mainly focuses on the MP and GMP composites and their structural behavior and contribution to the structural performance of concrete beams. Hence, the MP and GMP composites are produced and the mechanical characterization of the composites is conducted by tensile tests. Moreover, influences of graphene on the mechanical properties of the composites are investigated by using mechanical tests and Scanning Electron Microscope (SEM). Then, the physical and chemical properties of the cement are determined in the laboratory and the plain concrete (PC) beams are constructed. After the 28-day curing periods in a moist cure room, the mechanical properties of the PC beams are determined and the beams are strengthened with the composites following four different configurations with external and internal positioning. After the strengthening process, the mechanical tests are carried out on the strengthened beams and all beams are also analyzed by using nonlinear finite element analysis (FEA) in order to compare the experimental and numerical results.

2. Composite manufacturing and characterization

Modern technologies have greatly improved the efficiency of materials and their manufacturing. Composite materials, in particular, have proven their significance in the engineering community where they provide several advantages such as durability, corrosion and fatigue resistance, fire safety, short installation time, easy and fast handling, high strength-to-weight ratios and relatively low cost [7,21,23].

2.1. Monolayer prepreg composites

In parallel to the advancements in material science, new composite materials suitable for use in new and existing structures are emerging. Among these materials, the prepreg composites receive significant attention in terms of engineering applications. Prepreg (short for pre-impregnated reinforcement fibers) composites are polymer-based materials [48,49]. There are various types of prepreg composites, which can be classified into two main categories: a) traditional woven cloth that is resin impregnated allowing an easier processing for manufacturing parts in production lines, and b) unidirectional prepreg composite, which consists of continuous fibers [50,51]. Prepreg composites are very suitable for laminating process in the long term due to their long shelf life as frozen in a gel state. In this technique, end users might manufacture multi-laminated prepreg composites with a desirable number of plies by using vacuum bagging, autoclave or hot press methods. In this study, the monolayer prepreg (MP) unidirectional thin composite is used in order to investigate the effect of the prepreg material as an internal and external strengthening building material.

In the manufacturing of the MP composites, carbon fiber (12 K, with a code number A-42, DowAksa, Turkey) and epoxy system, which consists of the epoxy resin (Araldite®LY 1564 SP, Huntsman, USA) and the hardener (Aradur®XB 3486, Huntsman, USA) are used. A lab – scaled prepreg machine is used in the process, Fig. 1. The prepreg manufacturing process involves the drum winder technique by impregnating fibers with a resin system and heating the prepreg until the resin system reaches the gel state. In preparing the neat matrix material, the epoxy resin and the hardener are mixed in the ratio of 100:34, by weight. Afterwards, the carbon fibers are completely subjected to the matrix material and the resinous fibers are wound onto the drum as a single layer. Subsequently, the drum is heated at 80 °C for the gel time. The prepregs in the gel state are stored in a cold storage. After all the MP composites are manufactured with 0.125 mm thickness and kept in the deep freeze, the MPs are left to cure in room temperature (RT).

2.2. Graphene-reinforced monolayer prepreg composites

The generation of nanotechnology is one of the most important innovations of today. The nanomaterials that have nanoscale features have significantly become very popular in several industries and they are investigated in different scientific domains. Especially, the fabrication of graphene has contributed intensively to the advancements in nanoparticle studies [52]. Graphene is a single atom layered carbon and it is the first 2D crystalline and finest material in the world. A few layer graphene was fabricated by Geim and Novoselov in 2004 and its applications are spreading with a very fast pace [53,54]. Graphene may be modified with different techniques and it can be obtained from different graphene crystals such as single and multi-layered graphenes, graphene oxides, and nanoplatelets. These unique materials are heavily used in different engineering applications and they are generally preferred over the reinforced polymeric materials in order to improve the mechanical properties [55].

In the manufacturing of the GMP composites, epoxy system is filled with the graphene (with the code Grafen-iGP, Grafen Chemical Industries, Turkey). The graphene, which has 96–99% purity, 1% oxygen content, 5 to 44 μm diameter, and 50–100 nm in thickness is used in the GMP composites. In the matrix modification process, the graphene is sonicated within pure acetone by using an ultrasonic mixer (Hielscher UP400s, Germany) for almost one hour in order to prevent an agglomeration of graphene sheets. After dispersion, the acetone is removed in an oven. Then, graphene is inserted into the epoxy resin at a 1% of the weight of the epoxy system and the mixture is sonicated at 90 W for 15 min. Afterwards, the graphene/epoxy resin mixture is mechanically stirred with the hardener, Fig. 2. After the preparation of the graphene-modified matrix, the same prepreg manufacturing process with the MPs is performed in order to obtain the GMP composites. Finally, all the GMP composites are cured in RT and the average thickness of the GMP composites is measured as 0.125 mm.

2.3. Mechanical characterization of the composites

In this study, it is intended to investigate the structural morphology of the MP and GMP composites with SEM imaging. The MP and GMP samples are cut into 5 mm length and analyzed by