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Environmental Exposure Performance of a Panel-Type Glass-Fiber-Reinforced Polymer Composite Clamping Plate for an Improved Moveable Weir

개량형 가동보에 적용하기 위한 패널형 유리섬유보강 폴리머 복합재료 클램핑 플레이트의 환경노출 성능

Yoo Seong-Yeoul* · Jeon Jong-Chan* · Shin, Hyung-Jin** · Park Chan-Gi*,†
유성열 · 전종찬 · 신형진 · 박찬기

Abstract

The improved movable weir supplements the advantages and disadvantages of the rubber weir and the conduction gate. It consists of a stainless steel gate, air bags, and a steel clamping plate. The stainless steel gate is the main body of the weir, and the inflatable rubber sheet serves to support the steel gate. The steel clamping plate is typically in direct continuous contact with water, but this leads to corrosion issues that can reduce the life of the entire movable weir. In this study, a panel-type glass-fiber-reinforced polymer (GFRP) clamping plate was designed and fabricated. The test results showed that the flexural load of the panel-type GFRP composite clamping plate was over twice that of the wings type GFRP clamping plate. The lowest moisture absorption value was obtained upon exposure to tap water, and exposure to other solutions showed similar values. Additionally, flexural load testing after exposure to an accelerated environment found the lowest residual loads of 80.51 % and 78.50 % at 50 and 100 days, respectively, for exposure to a $CaCl_2$ solution, while exposure to other environments showed residual failure loads of over 80 % at both 50 and 100 days.

Keywords: Accelerated environment, Flexural load, Improved moveable weir, Panel-type GFRP composite clamping plate, Residual load

Ⅰ. Introduction

The improved movable weir has been used extensively in river projects since its development, and demand for it is increasing (Yeo et al., 2009; Park, 2010; Park et al., 2017; Kim et al., 2010; Kim, 2006). The conventional concrete fixed weir was used until the 1980s, but it had several drawbacks: it reduced the capacity for water control during flooding because of the deposition of earth and sand caused by the reduction in water speed on the upstream side of the fixed weir, and it polluted the water (Lee et al., 2011; Kim et al., 2015). Because of their loss of function, most concrete fixed weirs have been demolished or replaced with movable weirs (Choi et al., 2013; Choi et al., 2008). A movable weir consists of several parts: rubber weir, hydraulic conduction gate, opening/closing sluice gate, hinge-type automatic sluice gate, and an S&R movable weir (Kim, 2006; Lee et al., 2011). Demand has increased for the installation of rubber weirs and improved movable weirs (Choi, 2011; Lee et al., 2014; Hwang et al., 2008). The rubber weir is typically the pneumatic function type, which is based on the air intake/exhaust method (Lee et al., 2012). This design is eco-friendly because it does not discharge pollutants into the river, but it is weaker than the plate gate (Kim et al., 2015). The hydraulic plate conduction gate has excellent durability, but has the risk of polluting rivers with its hydraulic fluid (Lee et al., 2012). The improved movable weir supplements the advantages and disadvantages of the rubber weir and the conduction gate, and uses both an inflatable air bag and a steel plate (Kim et al., 2015). The stainless steel gate is the main body of the weir, and the rubber sheet is inflated to support the steel gate. The clamping plate fixes the rubber sheet to the base concrete. Currently, the clamping plate is installed on the rubber sheet in indirect contact with the water. Metals have typically been used to construct the

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* Koungju National University
** Rural Research Institute, Korea Rural Community Corporation
† **Corresponding author**
Tel.: +82-41-330-1266 Fax: +82-41-330-1260
E-mail: cgpark@kongju.ac.kr

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clamping plate of the improved movable weir (Kim et al., 2015). However, the clamping plate made of steel corrodes when in constant contact with water (Fig. 1a). Such corrosion may reduce the life of the entire improved movable weir (Kim et al., 2015). This study has considered a variety of approaches to solving the problem of clamping plate corrosion: in particular, using glass-fiber-reinforced polymer (GFRP) composites. Using these for the clamping plate of the improved movable weir would solve the corrosion issues and improve the ease of installation because of their much lower weight. To date, GFRP composites have been used in architectural structures such as bars, sheets, plates, and grids (ACI 440H, 2000; Peng et al., 2014; Jikai Zhou et al., 2011). They have been widely used as substitutes for steel bars because of their excellent corrosion resistance, for example, as the upper plate of bridges (João M. Sousa et al., 2014; Park et al., 2005; Saud Aldajah et al., 2009; Yasushi Miyano et al., 2004). GFRP composites have been proven to be effective stiffeners for structures in challenging environments because of their excellent specific strengths (strengths per unit weight) (Hugo C et al., 2014; Park et al., 2003; Micelli et al., 2001). Extensive research has been conducted on structural uses of GFRP composites (Scalici et al., 2015; Rami Haj-Ali et al., 2002). In addition, studies on fracture by general interface separation of GFRP composite using continuous filament mat layer have been carried out, and it has been found that horizontal failure occurs instead of failure of load direction (vertical direction) (Scalici et al., 2015; Rami Haj-Ali et al., 2002). The current study explores using a GFRP composite as the substitute for metal in clamping plate design. A GFRP clamping plate was attached to the rubber dam to improve its durability (Lee et al., 2011). However, problems occurred when the conventional GFRP clamping plate design was used in the improved movable weir; specifically, the wing-shaped parts at both ends were often damaged (Fig. 1b). Thus, it was necessary to develop a GFRP clamping plate that could overcome this problem.

This study designs and fabricates a panel-type GFRP clamping plate without wings. The conventional GFRP clamping plate used for the improved moveable weir should be changed only enough to solve only the fracture of the wing part while maintaining its existing role. This is because, if the overall shape of the GFRP clamping plate is changed, the shape of the improved moveable weir must be adjusted to the clamping plate. Our design eliminated the corrosion issue found with metallic clamping plates and damage to the wing parts since there were none in the design. In this study, the performance of a panel-type GFRP clamping plate was evaluated using destructive and durability tests, and its applicability for improving the durability of an improved movable weir was assessed.

II. Materials and Manufacturing

This study used E-glass fibers, a low-cost fiber with excellent mechanical characteristics, as the reinforcing fibers in a polymer matrix. The polymer matrix consisted of epoxy, vinyl ester, and polyester resin. Polyester resin is not suitable on its own for the clamping plate material, because it is easily

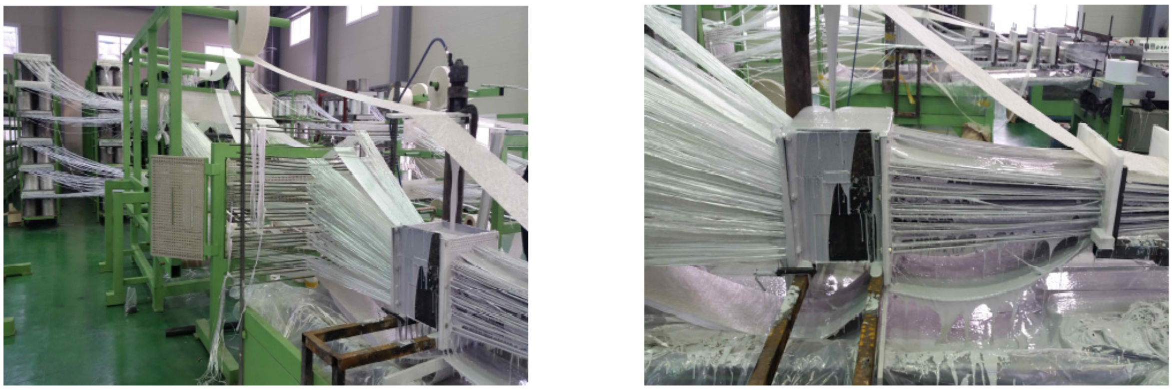
(a) Corrosion of steel clamping plate (b) Flexural geometry of wings-type GFRP clamping plate

Fig. 1 Clamping plate damage

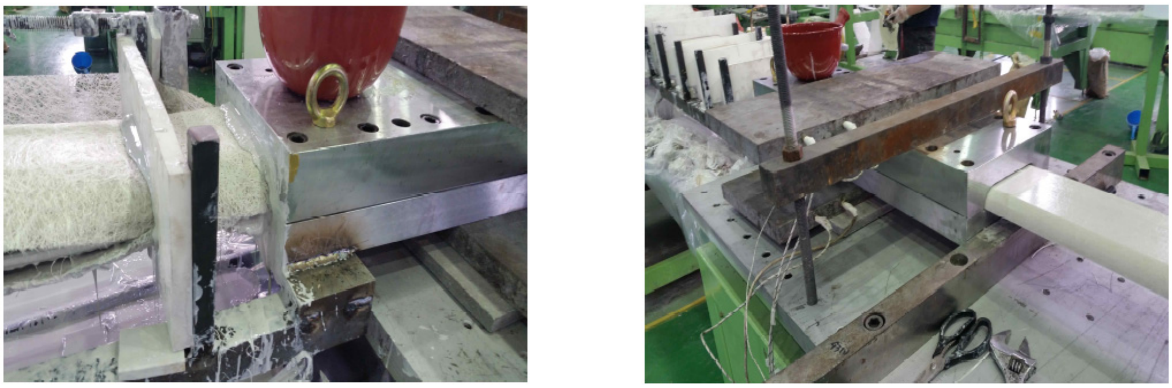
destroyed by OH ions. Vinyl ester resin is also affected by OH ions; however, ester-free products significantly reduce this weakness.[13] In this study, vinyl ester was used due to its low cost and excellent durability. Table 1 lists the characteristics of E-glass fibers and the vinyl ester resin used in this study. The mixture ratio for the GFRP material was 70 % E-glass fibers and 30 % vinyl ester resin by volume; pul-

Table 1 Mechanical properties of glass fiber and matrix resin

Mechanical properties	Vinyl ester resin	E–glass
Yield stress (MPa)	90	1,890
Elastic modulus (GPa)	3.4	71
Ultimate strain (%)	5.2	2.64
Fiber density (g/cm^3)	–	2.62
Fiber diameter (10–6 m)	–	16.5


(a) E–glass fiber supply

(b) Impregnation of vinyl ester resin


(c) Mold inlet supply after pre–forming

(d) Curing after molding passes


(e) Pulling device

(f) Cutting

Fig. 2 Manufacturing process of panel type GFRP clamping plate trusion was used to form the shapes.

The manufacturing process of the GFRP clamping plate presented by the producer is as follows. The plate was fabricated by the pultrusion process, which is a manufacturing method commonly used for the efficient mass production of high-quality products. The method consists of several batch processes, from the supply and arrangement of the reinforced fiber to cutting of the final product. The GFRP clamping plate was produced as follows. First, the glass fiber was arranged to form a laminated structure (Fig. 2a). The reinforcing fiber was then resin-impregnated through a guide slab that was designed according to the cross-sectional shape of the GFRP clamping plate (Fig. 2b). Passing the glass fiber through the resin ensured that the resin impregnated the pores between the fibers. Preforming was the third process (Fig. 2c). This was done for gradual deformation of the reinforced fiber impregnated with the resin through the guide slab, so that its shape would be close to the cross-sectional shape of the floor tube. The resin-impregnated reinforcing fiber was pre-molded before entering the mold, when excess resin was removed. The fourth process (Fig. 2d) continuously molded and hardened the shape in the electrically heated mold. The heating temperature (mold inlet temperature about 100 °C, mold intermediate temperature about 120 °C, mold exit temperature about 100 °C) was determined in consideration of the resin hardening speed (about 100 mm/min). The fifth process (Fig. 2e) consisted of pulling the molded GFRP clamping plate at a constant speed through the mold. The pultrusion speed was determined by the resin-hardening characteristics, mold temperature, and mold load. The final stage cut the plate to a specified length (Fig. 2f).

Ⅲ. Test Methods

1. Absorption

Different solutions were applied to the GFRP clamping plate to mimic the effects of seawater and sodium sulfate environments on the composite. The rate of absorption was measured using tap water, 10 % Na_2SO_4 solution, and 4 % $CaCl_2$ solution. The solution temperature was maintained at 60 °C to accelerate moisture absorption. In this study, weight changes were measured daily for the first 50 days, and every 5 days until day 100 for the second 50 days. The absorption rate was calculated by measuring the weight change of the clamping plate and using Equation 1:

$$M = \frac{W - W_d}{W_d} \times 100(\%) \tag{1}$$

where M indicates absorption rate (%), W wet weight, and W_d dry weight.

2. Flexural Load

A flexural test was used to evaluate the mechanical properties of the panel-type GFRP clamping plate. Because the plate fixes the air bag to the concrete base, the plate does not experience a tensile load, but instead shear and flexural loads. The adhesive interface between the glass fiber and the polymer resin is a sensitive region whose failure could lead to destruction of the weir. The test was conducted for the panel-type GFRP clamping plate. Fig. 3 shows a photograph of the flexural test using a universal testing machine with a capacity of 1,000 kN. The test speed was 1 mm/min and the span for the test was 300 mm. The test was carried out on six specimens.

3. Accelerated Environmental Conditions

Seven types of accelerated environmental conditions (tap water, 10 % Na_2SO_4 solution, 10 % $MgSO_4$ solution, and 4 % $CaCl_2$ solution, drying/wetting cycle, long term oven drying, freezing/thawing cycles, and long-term frozen) were used

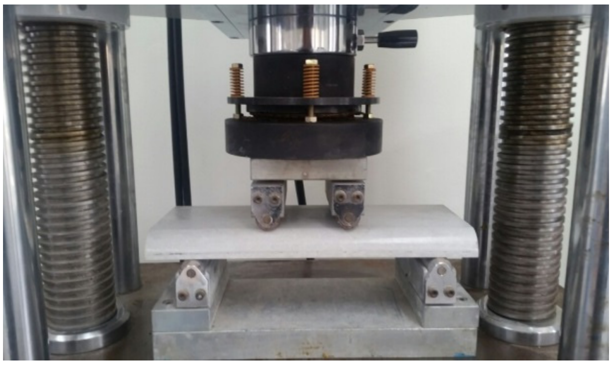


Fig. 3 Flexural load test set-up

to evaluate the durability of the GFRP composite clamping plate. The flexural test was conducted once environmental exposure was complete. The major reason for using a GFRP composite clamping plate is to solve the corrosion problem experienced by the conventional design that uses metal. The effects of the chemical environment were used to evaluate this issue. The composite was soaked in tap water, 10 % Na_2SO_4 solution, 10 % $MgSO_4$ solution, and 4 % $CaCl_2$ solution at 60 °C for 50 and 100 days.

The moveable weir undergoes both a wet state and a dry state for the summer water level change. Specifically, when using a modified moving panels, a panel of water is installed in the river to hold the water, and the panel is operated to control water flow. Therefore, when the water is confined, the weir is dry, and when the water flows, it is wet. A drying/wetting cycle test was used to evaluate the sensitivity of the GFRP composite to moisture. The possibility of surface damage of the composite is much higher when it is exposed to a cyclic dry/wet environment than when it is continuously exposed to moisture. Repeated wetting and drying cycles tests were carried out using the methods used in previous studies (Lee et al., 2011; Park et al., 2005). The composite was dried in a 60 °C oven for 24 h, and then soaked in 20 °C water for 24 h. This test was repeated 25 times for 50 days.

The thermal expansion coefficients of the glass fiber and resin used in the GFRP composite clamping plate are quite different, so that exposure to sufficiently high time/temperature combinations could lead to failure of the clamping plate. The plate was heated in an oven at 60 °C for 50 days to explore this issue.

The possibility of damage caused by repetitive freezing/thawing cycles was also considered because the rubber dam is exposed to such cycles in the winter. The composite clamping plate was thus subjected to 300 freezing/melting cycles and then assessed for damage according to the ASTM C666 standard.

In the winter, the plate could experience loading while frozen in the water, which could also cause damage. Therefore, the plate was frozen at -5 °C for 50 days, after which its mechanical properties were evaluated.

Ⅳ. Results and Discussion

1. Absorption rates

Fig. 4 shows the final absorption rate after 50- and 100-day exposures. Existing research on absorption characteristics after exposure to existing expedition environment suggests there is less than 2.0 % absorption when GFRP composites are applied as reinforcing materials of concrete (Park et al., 2003; Mieclli et al., 2001). For this study, the absorption rate of FRP clamping plate was evaluated by comparing it to that finding. Test results also showed the lowest water uptake in tap water and slightly increased uptake in other environments. The absorption rate of $CaCl_2$ was the largest. This result is similar to existing test results in a salt environment because corrosion due to the salt environment occurred (Dejke, 2001; Vijay, 1999). In the case of the $CaCl_2$ solution, surface corrosion was slightly increased due to the environment of the sulfate ion solution. However, the difference in the results was not significant. The test results indicated the highest absorption rate was about 0.58 % in the $CaCl_2$, Na_2SO_4, and $MgSO_4$ solutions, and it can be said to be stable as it showed relatively smaller absorption rate than 2.0 %.

2. Flexural load and accelerated environmental conditions

Fig. 5 shows the flexural test results for the panel-type GFRP composite clamping plate. Its load at flexural was more than twice as large as that of the wings-type GFRP clamping plate, namely, about 245 kN vs. 124 kN.

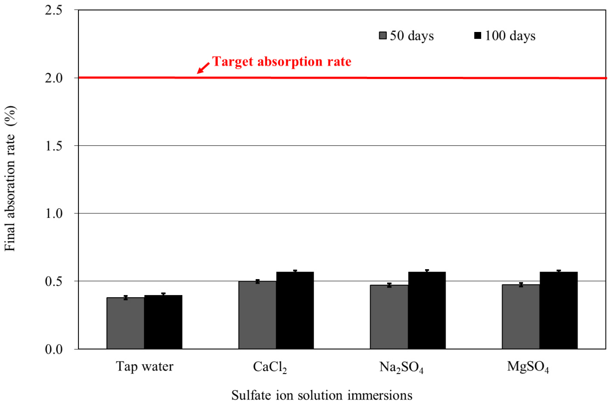


Fig. 4 Final absorption rate of GFRP clamping plate

For this study, the panel-type GFRP clamping plate was developed and its performance was evaluated in order to solve the problem that the wings of the wings-type GFRP clamping plate are destroyed by vertical cracks and tilted cracks. Therefore, in this study, the flexural load of the wings type GFRP clamping plate before exposure to the environment was set as the target load of panel type GFRP clamping plate after environmental exposure. Fig. 6 shows the results of the flexural testing of the panel-type GFRP clamping plate after exposure to various chemical environments. The average failure loads after exposure for 50 and 100 days were 218.56 and 212.92 kN for tap water, 213.97 and 207.98 kN for the Na_2SO_4 solution, 202.23 and 199.56 kN for the $MgSO_4$ solution, and 193.17 and 188.38 kN for the $CaCl_2$ solution. The load at failure after prolonged exposure was thus the lowest for the $CaCl_2$ solution. Also, the test results satisfied all of the target flexural loads (124 kN).

Fig. 7 shows results after the panel was exposed to different accelerated physical tests. The loads at failure after 50 and 100 days, respectively, were 211.24 and 192.88 kN for the drying/wetting cycle test, 204.32 and 196.67 kN for the long-term freezing temperature test, 237.13 and 228.14 kN for the long-term high-temperature exposure test, and 209.67 and 205.34 kN for the freezing/thawing cycle test. Also, the test results satisfied all of the target flexural loads (124 kN).

Fig. 8a compares the test results for exposure of the panel to the different chemical environments. The residual flexural loads after soaking in the $CaCl_2$ solution were 80.51 % and 78.50 % after 50 and 100 days, respectively. This solution gave the lowest residual loads, but all of the environments gave residual flexural loads exceeding 80 % at both 50 and 100 days. Fig. 8b shows the residual flexural load test results for the GFRP clamping plate exposed to the various accelerated aging environments of repetitive drying/wetting, long-term freezing, long-term high temperature, and cyclic freezing/melting. All of the samples had residual loads that exceeded 80 %. Compare this to the results of previous researches (Micelli et al., 2001), who studied the environmental reduction factor in applications of GFRP composite materials using 0.70 GFRP composites and achieved 75 % of residual tensile stress and over 65 % of residual ISS (interlaminar shear stress) (ACI 440H, 2000; Park et al., 2003; Micelli et al., 2001).

Fig. 9 shows the relationship between the moisture absorption rate and the residual load. The residual load decreased

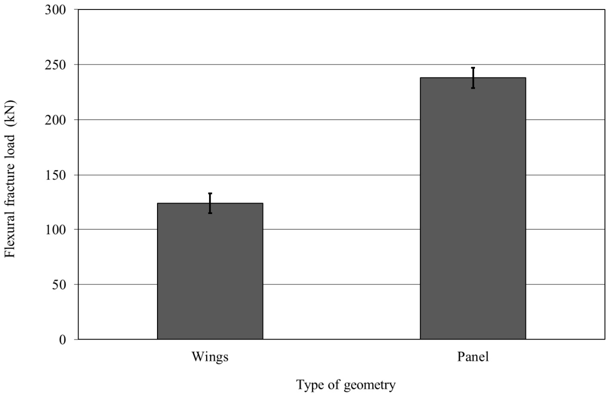


Fig. 5 Flexural load test results of GFRP clamping plate

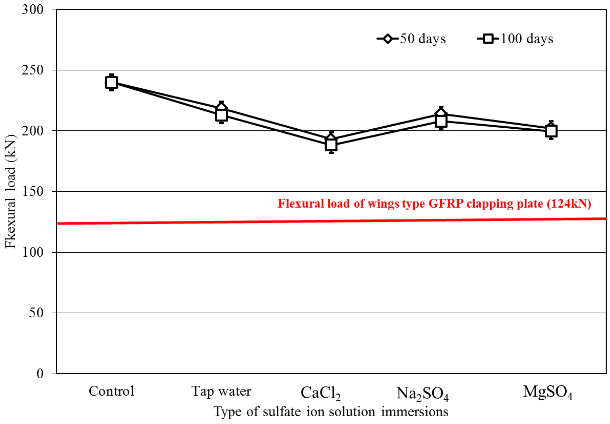


Fig. 6 Flexural load of panel type clamping plate after chemical solution exposure

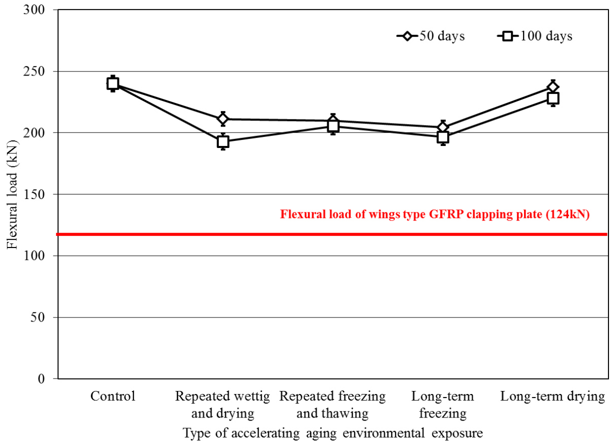
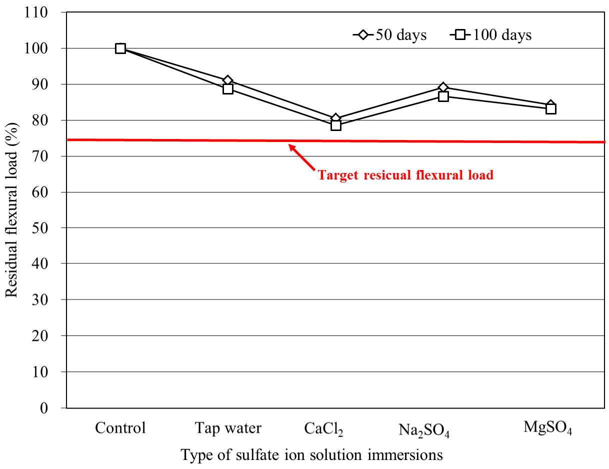
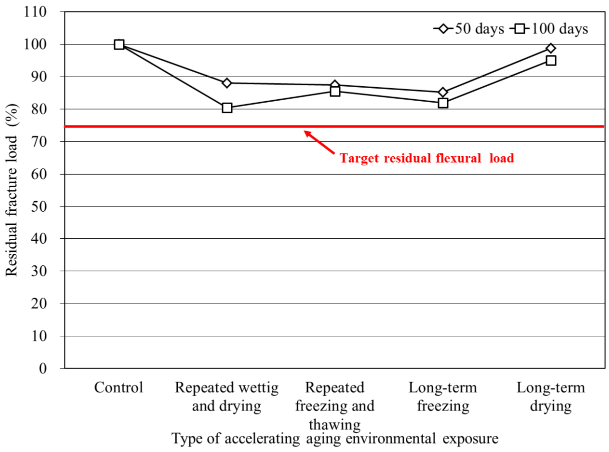


Fig. 7 Flexural load of panel type clamping plate after physical environments exposure



(a) Chemical solution exposure

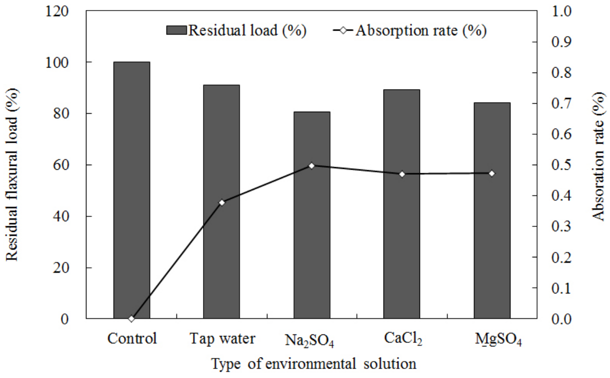


(b) Physical environmental exposure

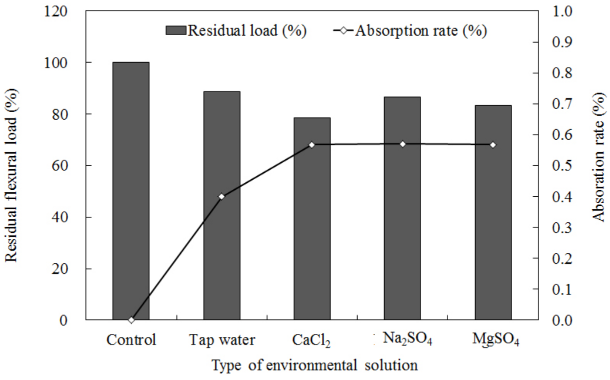
Fig. 8 Residual flexural load results of panel type clamping plates after environmental exposure

as the moisture absorption rate of the panel-type GFRP clamping plate increased. Generally, moisture absorption by the matrix resin caused damage at the glass fiber/matrix interface. Cracks generated inside the GFRP composites increased the moisture absorption rate and led to reduced residual loads (Dejke, 2001; Vijay, 1999). The GFRP clamping plate showed this phenomenon, and the residual strength decreased with increasing absorption rate.

V. Conclusions



(a) 50 days exposure



(b) 100 days exposure

Fig. 9 Relationship between residual load and absorption rate

A panel-type GFRP composite clamping plate without wings was designed and fabricated for this study. The design overcame two significant shortcomings of conventional clamping plates: metal corrosion and damage to the wings. Moisture absorption, destructive, and durability tests were conducted to evaluate its performance. The test results are summarized as follows:

(1) Flexural load testing showed that the value for the panel-type GFRP composite clamping plate was over twice that of the wings-type GFRP clamping plate. The latter had an average flexural load failure point of about 124 kN, while the panel-type GFRP clamping plate had a value of about 245 kN.

(2) The lowest moisture absorption rate was obtained during exposure to tap water; soaking in the other liquids gave similar values.

(3) Flexural load testing after exposure to accelerated environments produced residual failure loads that exceeded 80 % after 50 and 100 days of exposure in all cases. The smallest residual load was observed for the plate soaked

in CaCl solution, namely, 80.51 % and 78.50 % at 50 and 100 days, respectively.

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