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Study on application of fiber-reinforced concrete in sluice gates

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HIGHLIGHTS

- The sluice gate is made by concrete and applied it in hydraulic engineering.
- The concrete gates meet operational needs and watertight seals functioned normally.
- The concrete gate is as cheap as one-fifth cheaper to produce than cast iron gates.

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ABSTRACT

A sluice gate is a primary hydraulic structure in water discharge and storage facilities. Steel sluice gates are often stolen when global metal prices are high. Thus, this study proposed using fiber-reinforced concrete to fabricate sluice gates. The material mechanical properties and durability of the fiber-reinforced concrete sluice gates were tested, and field test and feasibility tests were subsequently performed. The compressive strength, flexural strength, and elastic modulus of the concrete used to construct the gates were respectively 99.3 MPa, 18.2 MPa, and 40.0 GPa. In the concrete, the depth of wear by hyperconcentrated flow was 0.5 mm h^{-1} mm^{-2}; the chloride diffusion coefficient was 2.25×10^{-12} m^2 s^{-1}; and the weight loss in the soundness test was 1.02%.

The results of the field testing suggested that the size and weight of the fiber-reinforced concrete sluice gates met operational needs and that the gates maintained their watertight seals and functioned normally during and after several tropical cyclones. Monthly observations revealed no noticeable cracks or rust stains on the gate surfaces. And the difference of properties of fiber-reinforced concrete before and after one year exposure is within ±6%. The fiber-reinforced concrete sluice gates were estimated to be one-tenth cheaper to produce than stainless steel gates and one-fifth cheaper than cast iron gates. The concrete sluice gates can be employed in low-head areas and drainage basins.

1. Introduction

A sluice gate is a hydraulic structure that controls flood water, affords protection against tides, and channels and stores water. Its operation and management is fundamental to ensuring the safety of the lives and property of the general public. The number of sluice gates across Taiwan has been increased since the government performed improvement works on river drainage canals and flood-prone detention basins and pumping stations. Sluice gates in Taiwan are mostly made of metal (including cast iron, black iron, and stainless steel); they are frequently stolen and sold as scrap metal because global metal prices continue to rise, pushing scrap metal prices higher. Such thefts are more common in sparsely populated regions [1]. An additional problem is that bulky steel sluice gates make it difficult to discharge water inside of levees. Malfunctioning sluice gates inhibit efforts to prevent floods, thus threatening public safety and property. This underlines the need to develop nonsteel sluice gates that have lower dead weight, are less likely to be stolen, and can facilitate water discharge.

Concrete is characterized by high strength, density, durability, and modulus of elasticity and low permeability and cost; it also weighs much less than steel. Fiber-reinforced concrete (FRC) is a composite concrete material containing uniformly distributed fibers whose high tensile strength helps to prevent the material from rupturing internally and enables it to withstand the extension of cracks. FRC is thus stronger and more resistant to cracks, impacts, shocks, and abrasion than normal concrete [2–5]. In the present study, concrete was used to construct sluice gates, the mechanical properties, durability, and cost of which were assessed. The findings of this study can be applied in hydraulic engineering.

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2. Design and construction of concrete sluice gates

A sluice gate traverses a river or water course and comprises civil engineering components, a gate unit, and a mechanical lifting system [6]. Specifically, the structure consists of the following: (1) a gate (a movable device that comprises a body structure, frame, and fixation base and is usually made of steel); (2) culvert (embedded underground and crossing flood-prevention roads and levees, it connects discharge canals inside of a riverbank and river drainage structures outside of the bank and comprises one hole at the entrance and another at the exit); (3) lifting device or winch (opens and closes the gate mechanically and is driven manually, electrically, or hydraulically); and (4) derrick (made of metal to connect the gate and the hoist, and built in the shape of a screw thread or trapezoid). Fig. 1 is an illustration of a sluice gate. A sluice gate can be operated either automatically or manually. Automated sluice gates, normally installed on levees and banks to prevent tides and floods, use pressure from water-level differences between the inside and outside of a bank to release their self-weight pressure and prevent tidewater intrusion. Manual sluice gates require human operators to use a winch to actuate a derrick, thereby opening and closing the gate vertically, and are typically installed at ditches or rivers for regional sewage and field irrigation [6]. In this study, the proposed FRC sluice gates were operated automatically.

Because of safety concerns, the sluice gate were installed 739 m away from the starting point of the Houanliao sea embankment at the Mailiao Estuary in western Taiwan (Fig. 2) and 2110 m away from the starting point of the Tanduliao river embankment at the Sandie River in southwestern Taiwan (Fig. 3). For the sake of brevity, the FRC sluice gate installed at the Houanliao sea embankment is referred to herein as the Houanliao sluice gate, whereas that installed at the Tanduliao river embankment is named the Tanduliao sluice gate.

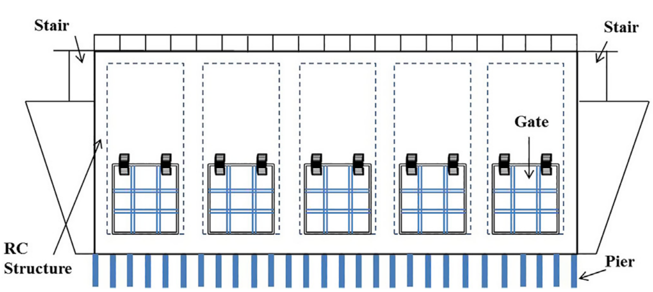

Fig. 1. Illustration of the sluice gate.

2.1. Design of FRC sluice gates

FRC sluice gates were designed in accordance with the technical standards for sluice gates and iron tubes that were developed by Japan Electric Power Civil Engineering Association [6]. The design load of the sluice gates comprised hydrostatic pressure, hydrodynamic pressure during earthquakes, inertial force during earthquakes, mud pressure, buoyancy, impact force from driftwood and other drifting objects, and flowing and static pressure during mudslides. On the basis of two-way slab theory, the maximum principal stress, maximum strain, and shear stress of the sluice gates were estimated, and the amount of steel reinforcement required in the structures was specified. Table 1 shows the results of the strain–stress analysis of the sluice gates.

Two FRC sluice gates were installed respectively at the Houanliao sea embankment and the Tanduliao river embankment, and their respective dimensions were $1700 \times 1700 \times 80\ mm^3$ and $1050 \times 1050 \times 60\ mm^3$ in length, width, and thickness. Both sluice gates contained a double-layered galvanized wire mesh (with wire diameter 2.6 mm, mesh spacing 26 mm, and ultimate tensile strength 2600 MPa) and a 15-mm-thick clear cover. Moreover, 3-mm-thick steel plates were welded within 250 mm in length and width from the center of the lifting lugs to increase the amount of steel reinforcement in the lugs and secure them more tightly.

2.2. Construction of FRC sluice gates

2.2.1. Material composition and specification

The sluice gates comprised the following materials: water; common Portland Type I cement; fine aggregates (derived from natural sand in the Dadu River in central Taiwan; specific gravity of 2.621, water absorption of 1.33%, fineness modulus of 2.98, and silt content of 6.44%); compressed silica fume (imported from Norway; silica content of 92.15%, loss on ignition of 1.75%, and passes 91.93% through a #325 sieve); water-quenched slag powder (produced by CHC Resources Corporation; specific gravity of 2.89); F-class fly ash (produced by the fifth and sixth generators at Tai-

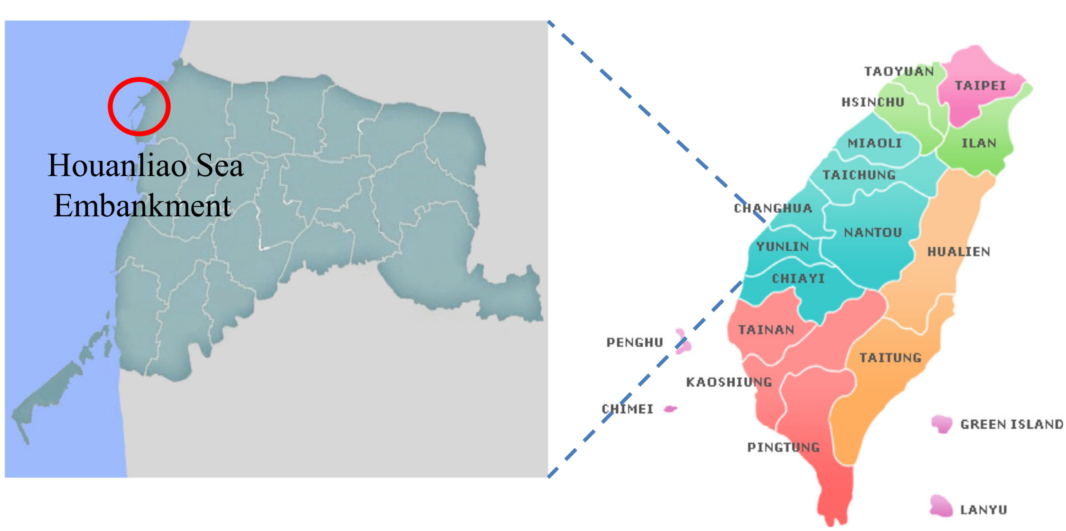

Fig. 2. Location of FRC sluice gate, installed 739 m away from the starting point of the Houanliao sea embankment at the Mailiao Estuary.

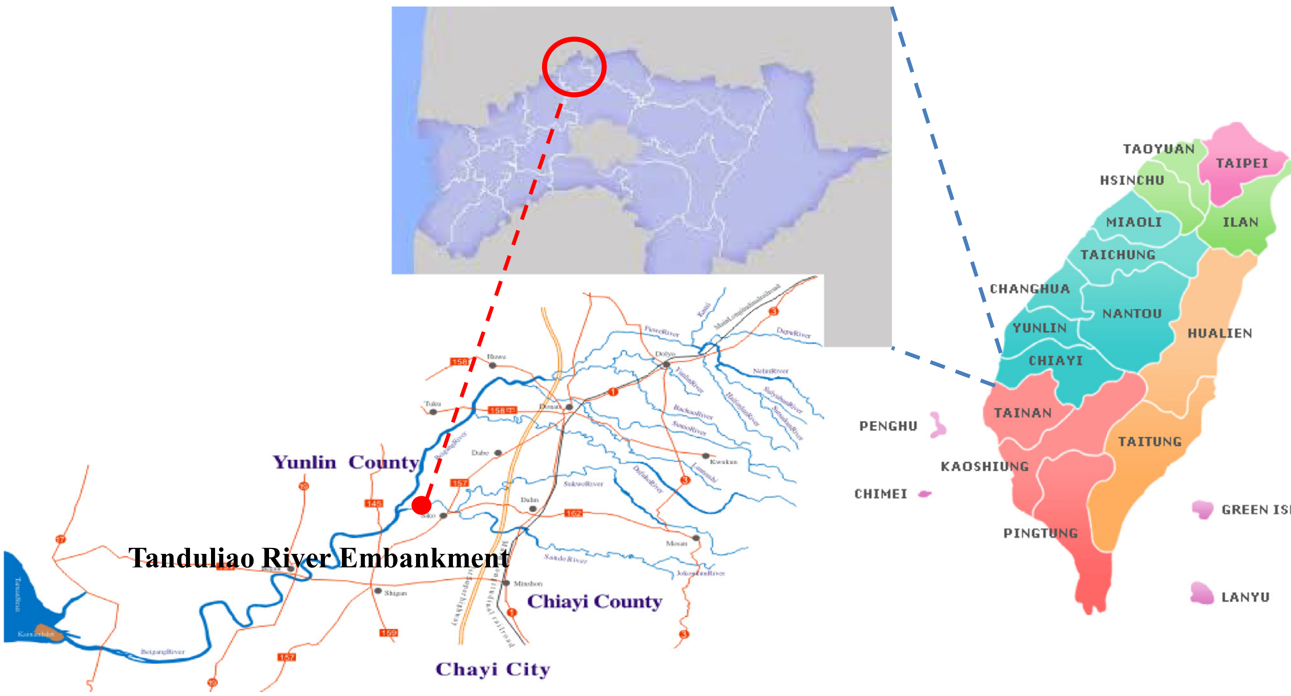

Fig. 3. Location of FRC sluice gate, installed 2110 m away from the starting point of the Tanduliao river embankment at the Sandie River.

Table 1
Results of stress–strain analysis of FRC sluice gates.

Stress	Houanliao sluice gate	Tanduliao sluice gate
Maximum principal stress (location)	5.37 MPa (near lifting lugs) −2.67 MPa (slightly below the center of the gate)	8.78 MPa (near lifting lugs) −5.33 MPa (slightly below the center of the gate)
Maximum shear stress (location)	1.16 MPa (near lifting lugs)	2.23 MPa (near lifting lugs)
Maximum displacement (location)	0.31 mm (slightly below the center of the gate; permitted displacement: 1700 mm/8000 = 2.1 mm)	0.35 mm (slightly below the center of the gate; permitted displacement: 1050 mm/8000 = 1.3 mm)

chung Power Plant); TAIRYFIL carbon fibers (produced by Formosa Plastics Group; specific gravity of 1.8); and Type G superplasticizer (HICON MTP-A40; specific gravity of 1.1). Table 2 shows the composition of fiber-reinforced concrete.

The water/cementations material ratio (w/cm) was set to be 0.26, and the percentage of coarse aggregate per unit volume of concrete (m^3/m^3) used was 35% (with a Los Angeles abrasion loss of <40%). The slump of newly mixed concrete was 20 ± 2 cm, so that no exudation or aggregate segregation occurred.

2.2.2. Construction and curing of concrete sluice gates

The construction of the FRC sluice gates involved fabrication of a wooden mold, arrangement of galvanized wire meshes, welding of steel plates and mixing of concrete, and preparation of set bolts around the sluice gate for the installation of rubber water seals. Once these steps had been completed, concrete pouring began. During concrete pouring, a vibrator was used to compact the concrete and a trowel was subsequently employed to flatten the concrete. The resultant concrete was demolded one day after its preparation and underwent moist curing for 28 days. Before the concrete sluice gates were installed at the frame of the outlet of embankments, set bolts were prepared around the sluice gates for the installation of rubber water seals to render the sluice gates watertight. In this study, P-type nonporous gate water seals were employed, as shown in Figs. 4–6. And Fig. 7 shows that both freshly constructed FRC sluice gates had a fairly smooth surface and contained few visible bubbles or pores.

2.3. Properties of the concrete

The slump flow of FRC was tested according to ASTM C143. Air content and unit weight were tested according to ASTM C138. The results of the mixing show that the FRC did not occur in the case of separation and bleeding. The result of the slump flow test is 67 cm, the slump test result is 24 cm, the air content of fresh concrete is 2.0% and the unit weight is 2373 kg/m^3. The compressive strength (ASTM C39), flexural strength (ASTM C78), splitting tensile strength (ASTM C496), elastic modulus (ASTM C469), and coefficient of thermal expansion (AASHTO T336) of the FRC were respectively 99.3 MPa, 18.2 MPa, 7.6 MPa, 40.0 GPa, and 2.16×10^{-5} °C^{-1}. The test results of mechanics properties have shown as Table 3.

Table 2
Composition of FRC sluice gate material (kg/m^3).

w/cm	Water	Cement	Slag powder	Fly ash	Coarse aggregates	Carbon fiber	Fine aggregates	Superplasticizer
0.26	160	400	140	75	917	8	586	6

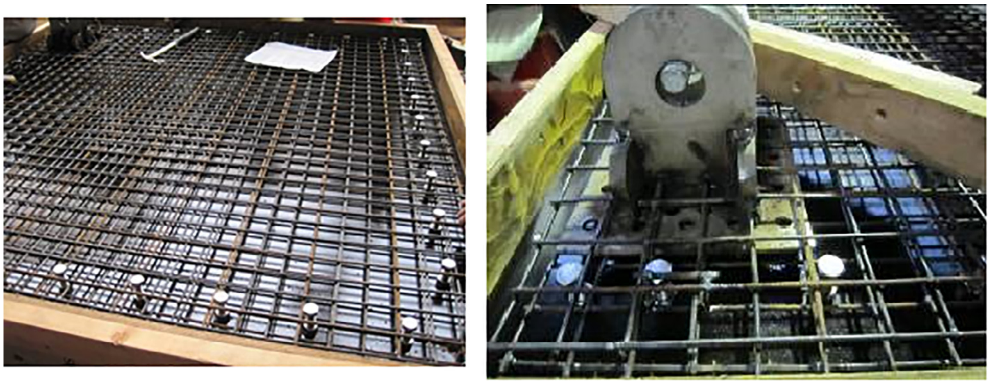

Fig. 4. Locations of lifting lugs in relation to the wire mesh.

Fig. 5. Concrete pouring.

Fig. 6. FRC sluice gates installation water seal.

Fig. 7. Surface of the demolded FRC sluice gates.

Table 3
Test results of mechanics properties of fiber-reinforced concrete.

Test Item	Test Method	Unit	No.1	No.2	No.3	Average
Compressive Strength	ASTM C39	MPa	102	99	97	99.3
Flexural Strength	ASTM C78	MPa	18.4	18.0	18.1	18.2
Splitting Tensile Strength	ASTM C496	MPa	7.6	7.9	7.3	7.6
Elastic Modulus	ASTM C469	GPa	37.7	40.7	41.6	40.0
Coefficient of Thermal Expansion	ASTM T336	$\times 10^{-5}$ °C^{-1}	2.14	2.15	2.19	2.16

The rate at which the length of the FRC changed (ASTM C157) was 0.006 at an age of 7 days, 0.005 at 14 days, 0.004 at 21 days, and 0.005 at 28 days. This indicated that the size of the concrete began to stabilize after 21 days, and the total length change in the concrete over 28 days was found to be 0.062 mm, within the permitted gate size error (4.5 mm) specified in the inspection guidelines published by the Japan Association of Dam and Weir Equipment Engineering [6].

The results of the durability test can be figured out with Fick's second law in Fig. 8 after a 90-day salt-ponding test (ASTM C1543). Which shown that the chloride diffusion coefficient of the concrete was 2.25×10^{-12} m^2 s^{-1}. According to Fick's second law of diffusion, when the atmospheric chloride concentration of a structure is lower than 0.05% and the chloride diffusion coefficient of concrete used in the structure is lower than 3×10^{-12} m^2 s^{-1}, it will take approximately 50 years for chloride ions to reach the surface of rebars via concrete pores. After it was alternately exposed five times to dry and wet impregnations using sodium sulfate, the concrete had lost 1% of its weight and had a compressive strength loss of 0.9. Accordingly, the concrete used in this study met the service life requirements of typical structures, had low weight and compressive-strength losses before and after robustness testing, and therefore exhibited high resistance to sulfate erosion.

The method of impact test for boards of buildings (CNS 9961), was employed to test the ability of the concrete plates to withstand impacts. In this method, a 13.5 kg steel ball was dropped on the center of a concrete specimen from a distance of 200 cm. The bottom of the specimen was supported on four sides, as shown in Fig. 9. The impact test was repeated until any visible crack formed or until deformation of the specimen occurred; the total number of impacts until this point was used as a measure of the concrete's impact-resistant capability. A pure concrete specimen and a fiber-reinforced concrete specimen were used in the impact test.

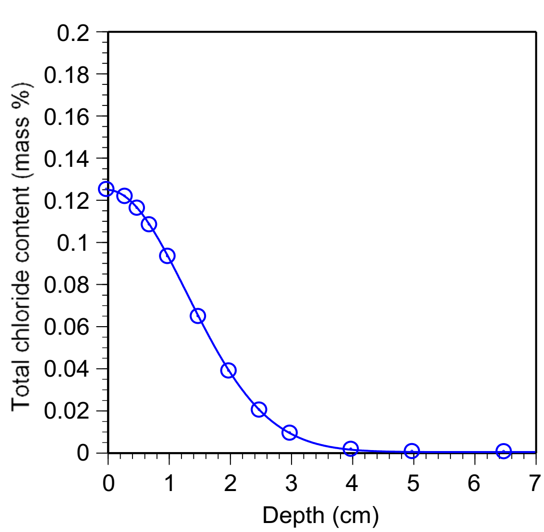

Fig. 8. Test result of ponding test of fiber-reinforced concrete.

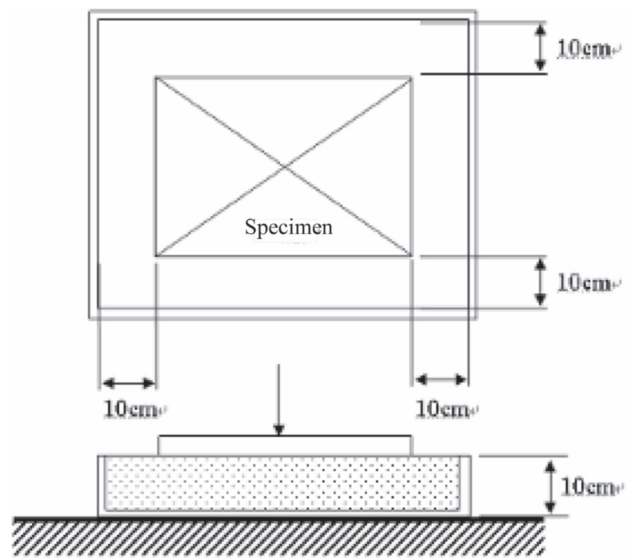

Fig. 9. Test apparatus of impact test for boards of buildings.

Both had dimensions of $500 \times 500 \times 60$ mm^3 and contained double-layered galvanized wire meshes. Small cracks formed on the ferrocement specimen after 8 impacts and on the fiber-reinforced concrete specimen after 28 impacts, as shown in Fig. 10. Thus, brittle fracture was less likely to occur on the surface of fiber-reinforced concrete sluice gates containing double-layered galvanized wire meshes when they were impacted by driftwood or other drifting objects.

3. Field test installation of FRC sluice gates

3.1. Field test installation

After FRC sluice gates were constructed and cured, their appearance and size were inspected in accordance with technical standards for sluice gates. The appearance inspection focused on the lifting lugs and whether the gate surface was smooth or had any scars or cracks. The size inspection examined the width, height, and thickness of the sluice gates, the length differential between both diagonals of the gate surface, and the center-to-center distance between lifting lugs. The results of both inspections suggested that the FRC sluice gates met specifications, with errors in size within the tolerance (<4.5 mm). After the sluice gates had met all the requirements of the inspections, they were delivered for field test installation. During their delivery, the sluice gates were securely fastened on pallets in a pickup truck to prevent them from being damaged due to shaking or sliding.

Once the sluice gates were completely installed, their horizontality and perpendicularity were properly adjusted and their tightness assessed. Whether the gates opened and closed smoothly and whether any abnormal sound was heard during their operation was also tested. Abnormalities were remedied wherever they

Ferrocement specimen Fiber-reinforced concrete specimen

Fig. 10. Concrete specimens produced cracks after the impact test.

Fig. 11. Installation of Houanliao sluice gate.

Fig. 12. Installation of Tanduliao sluice gate.

occurred. Figs. 11 and 12 show the installation process and the completion of the process, respectively.

3.2. Visual inspection

Both FRC sluice gates were completely installed on November 2, 2011, and were returned to our laboratory on November 5, 2012. The field test of the sluice gates comprised visual and durability inspections. The visual inspection was performed monthly; it focused on whether the gate surface had sustained any damage, any tears had formed around the lifting lugs, and rust stains had formed. The results of the inspection were photographed, and the locations, length, and area of tears were recorded. Water samples were obtained from the bodies of water near the installation sites to estimate the amount and pH of chlorine present. After the fourth-quarter visual inspection was completed, the sluice gates were returned to our lab for corrosion testing.

Visual inspection was performed at least once a month. The frequency of the inspection was adjusted judiciously in the wake of heavy rains or typhoons. For example, an inspection was per-

Fig. 13. The appearance of the Houanliao sluice gate (after 12 months of field testing).

Fig. 14. The appearance of the Tanduliao sluice gate (after 12 months of field testing).

formed after Typhoon Talim on June 12, 2012 when flooding was in progress (maximum daily rainfall of approximately 300 mm and total rainfall of more than 1000 mm) and after the flood waters had receded. After 12 months of field testing, the appearance of the Houanliao and Tanduliao sluice gates, as shown in Figs. 13 and 14, respectively.

The visual inspection revealed no damage to the surface of the FRC sluice gates after 1 year, during which time the temperature had been 15–29 °C, the total rainfall 789.5 mm, and the relative humidity 72%–86%. One flood (which occurred on June 12, 2012) and a few tropical cyclones occurred during this period. Notably, although the Houanliao sluice gate was constantly struck by flood and ebb tides, with more than one-third of its body constantly under seawater, its lifting lugs and surface exhibited no corrosion or rust stains. Similarly, despite having been soaked in wastewater from local pickling factories for a long period of time, the Tanduliao sluice gate showed no corrosion, had no cracks, was still functioning normally, and no damage or rust stains were present on its surface or lifting lugs after the high riverbank outside the embankment had been flooded on June 12, 2012.

4. Results of testing of FRC sluice gates after one year of use

After having been field tested for one year, both FRC sluice gates were removed and returned to the laboratory. The appearance and size of the sluice gates were inspected. The corrosion of the rebars and wire meshes in the sluice gates was also assessed. The results of the inspection and assessment were used to inform the design and construction of subsequent FRC sluice gates.

4.1. Appearance inspection

The objective of this inspection was to detect the presence of cracks and rust stains on both FRC sluice gates after they had been in use for one year. Specifically, the inspection focused on whether the cutting and welding of the lifting lugs and their bases met specifications; whether the edges on the lifting lugs and their bases were deburred; whether the gate surface was even; and whether any scars or cracks existed on the surface. Fig. 15 presents photographs of the sluice gates after they were removed for inspection. The Houanliao sluice gate had no cracks or rust stains, and its lifting lugs and water seals had not rusted or sustained any damage. However, the sluice gate was covered with barnacles and oyster shells up to 1200 mm from its bottom. Water-table measurements made by the supervisor of the Houanliao sea embankment suggested that the area of the sluice gate to which the marine creatures were attached had been frequently under seawater, indicating a high-tide level of 570–1200 mm. After the creatures were removed from the gate surface using manually operable tools such as shovels, the surface was found to be smooth. The surface of sluice gates at the Houanliao location should thus be cleaned annually, lest barnacles and oyster shells grow excessively on them, inhibiting their operation. Table 4 presents the results of the appearance inspection of the sluice gate in question.

4.2. Size inspection

The size inspection examined the width, height, and thickness of the Houanliao sluice gate, the length differential between the diagonals of the gate surface, and the center-to-center distance between lifting lugs. The results of the size inspection indicated that the sluice gate met its design specifications, and its errors in size were within the tolerance (<4.5 mm).

4.3. Assessment of the corrosion of rebars

One edge of both FRC sluice gates was drilled so that the corrosion of their rebars and wire meshes could be assessed (Fig. 16).

Fig. 15. Appearance of FRC sluice gates after they were removed from their embankments.

Table 4
Results of appearance inspection of Houanliao sluice gate.

No.	Item	Outcome
1	The cutting and welding of lifting lugs and their bases meet specifications.	Yes
2	Edges on lifting lugs and their bases are deburred.	Yes
3	There is no damage of any sort to the lifting lugs and their bases.	No
4	There are no uneven areas on the surface.	No
5	There are no scars or cracks on the surface.	No
6	The surface is free from deformation.	Yes

Fig. 16. Drilling one edge of sluice gate to assess the corrosion of rebars and wire meshes.

Fig. 17. Corrosion in Houanliao sluice gate.

The corrosion found in the Houanliao and Tanduliao sluice gates is displayed in Figs. 17 and 18, respectively. No corrosion or rust was discovered on the rebars or wire meshes of the sluice gates after 1 year. Corrosion in the sluice gates was assessed using drill holes as working electrode contacts (Fig. 19). The assessment of corrosion current and potential at nine assessment points on each sluice gate indicated no corrosion of rebars or wire meshes. The corrosion current approached 0 $\mu A\,cm^{-2}$ or was lower than 0.1 $\mu A\,cm^{-2}$; the corrosion potential exceeded −200 mA. Thus, the probability of corrosion in the sluice gates was <10%.

4.4. Mechanics properties of fiber-reinforced concrete after one year exposure

When the FRC sluice gate field testing carried out, the same proportion of concrete specimens placed in the vicinity of the sluice

Fig. 18. Corrosion in Tanduliao sluice gate.

Fig. 19. Assessing corrosion in FRC sluice gates.

Table 5
Test results of fiber-reinforced concrete after one year exposed.

Test Item	Test Method	Before	After	
			Tanduliao sluice gate	Houanliao sluice gate
Compressive Strength	ASTM C39	99.3 MPa	101.6 MPa	97.2 MPa
Splitting Tensile Strength	ASTM C496	7.6 MPa	7.9 MPa	7.2 MPa
Elastic Modulus	ASTM C469	40.0 GPa	39.1 GPa	40.3 GPa
Chloride Diffusion Coefficient	ASTM C1543	2.25×10^{-12} m^2 s^{-1}	2.33×10^{-12} m^2 s^{-1}	2.38×10^{-12} m^2 s^{-1}

Table 6
Properties of different types of sluice gates.

Property	Stainless steel	Cast iron	FRC
Material property	Rigid	Rigid	Tough
Resistance to impact	Excellent	Good	No cracks or deformation after one year in use
Resistance to acids, alkalis, and salt	Prone to rust stains	Prone to corrosion if installed near the sea	High
Weatherability	High	High	High
Specific gravity	7.93	7.85	2.4
Maintenance	Should be annually painted and cleansed of attached marine creatures	Should be de-rusted, painted, and cleansed of attached marine creatures every 6 months	Should be cleansed of attached marine creatures every 6 months
Service life	15–20 years (if installed in the tidal zone)	10–15 years (if installed in the tidal zone)	>30 years
Salvage value (New Taiwan Dollar per kilogram)	40–45	10–15	0
Probability of being stolen	High	High	Low
Manufacturing cost (1 m^2) in New Taiwan Dollars (the cost does not include gate frames, water seal, or lifting lugs)	70,000–80,000 for a 6-mm-thick gate	40,000–50,000 for a 6-mm-thick gate	8000 for a 80-mm-thick gate
Lead time	3–5 days	3–5 days	28–30 days

gate to study the mechanical properties after one year exposure. Table 5 showed the difference properties before and after one year exposure. It can be found in the table that no matter in Tanduliao or Houanliao, the difference between the results before field testing and after one year exposed is within ±6%. This shows that the mechanical properties of concrete are relatively small influenced by the field testing environment.

5. Recommendations regarding material use and construction methodology for FRC sluice gates

Neither field nor lab tests revealed cracks, chips, or corrosion in the Houanliao sluice gate (8 cm in thickness) or Tanduliao sluice gate (6 cm in thickness). Operating in the same manner as their steel counterparts, the FRC sluice gates can be employed in automated water gates with a height of less than 250 cm.

Table 6 compares the properties of stainless steel, cast iron, and FRC sluice gates. Compared with its stainless steel and cast iron counterparts, the FRC sluice gate has comparable properties but lower specific gravity and salvage value. Notably, FRC sluice gates have higher resistance to acids, alkalis, and salt; cost less to maintain and manufacture; have longer service life; and are less likely to be stolen. In addition, their low specific gravity does not cause their dead weight to decrease. This is because the protective cover of FRC sluice gates is adequately thick, making it heavier than stainless steel and cast iron sluice gates of the same size.

6. Conclusions

1. Sluice gates composed of FRC and double-layered wire meshes are proposed. After sluice gates were installed, they weathered several hydrologic events. Despite this, monthly observations discovered that the gates had no noticeable cracks or rust stains, functioned normally, and maintained their watertight seals. Thus, the sluice gates were operational considering their size and weight specifications.
2. During the construction of the FRC sluice gates, the percentage of coarse aggregate per unit volume of concrete (m^3/m^3) should be set to be at least 35%, with a Los Angeles abrasion loss of <40%.
3. After one year of use, both the Houanliao and Tanduliao sluice gates were removed from their respective embankments and returned to our laboratory for comprehensive inspection. The Houanliao sluice gates had barnacles and oyster shells attached at the bottom but exhibited no noticeable deformation, wear, or cracks. Both sluice gates were concluded to have been highly resistant to the impact of water flow.
4. The results of corrosion current and potential on the rebars and wire meshes of both sluice gates indicated no corrosion. Thus, these sluice gates, which had a 20-mm-thick protective cover and comprised FRC, afforded adequate protection for the rebars within.
5. No matter in Tanduliao or Houanliao, the difference between the compressive strength, splitting tensile strength, elastic modulus and chloride diffusion coefficient before field testing and after one year exposed is within ±6%.
6. The fiber-reinforced concrete sluice gates were one-tenth the cost of the stainless steel sluice gates and one-fifth the cost of cast iron ones. FRC sluice gates are less likely to be stolen because of their zero salvage value. In addition, they can be employed in low-head areas and drainage basins.

Conflict of interest

The authors declare that they have no conflict of interest.

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