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Research Article

Sustainability Assessment of Precast Ultra-High Performance Fiber Reinforced Concrete (UHPFRC) Cantilever Retaining Walls

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Abstract: This study evaluates the environmental impacts of a newly designed precast Ultra-High Performance Fiber Reinforced Concrete (UHPFRC) cantilever retaining wall as a sustainable alternative approach compared with the conventional precast Reinforced Concrete (RC) cantilever retaining wall. Nowadays, according to the shocking reports of many researchers worldwide global warming is one of the most devastating problems of human being. To date, lots of research has been undertaken in the concrete industry to tackle this issue through reducing the environmental footprints of our structural designs. In this regard, UHPFRC technology offers substantial benefits through efficient use of materials as well as optimization of the structural designs resulting less CO_2 emissions, Embodied Energy (EE) and Global Warming Potential (GWP). UHPFRC as a sustainable construction material is mostly appropriate for the use in the fabrication of precast members such as precast concrete cantilever retaining walls. This study demonstrates the overview of the designed precast concrete cantilever retaining wall manufactured from UHPFRC and its Environmental Impact Calculations (EIC) versus the conventional precast RC cantilever retaining walls. Based on the EIC results, the precast UHPFRC cantilever retaining walls are generally more environmentally sustainable than those built of the conventional RC with respect to the reduction of CO_2 emissions, EE and GWP. In summary, the precast UHPFRC cantilever retaining wall proposed in this study is an alternative sustainable solution compared with the conventional precast RC cantilever retaining wall which can be used in many civil engineering projects.

Keywords: CO_2 emissions, Embodied Energy (EE), Global Warming Potential (GWP), precast cantilever retaining wall, sustainability, Ultra High Performance Fiber Reinforced Concrete (UHPFRC)

INTRODUCTION

Nowadays, there are many concerns worldwide over the environmental impacts such as CO_2 emission, Embodied Energy (EE) and Global Warming Potential (GWP) of our structural designs due to the increased public understanding of the devastating effects of global warming. It is believed that cement production contributes almost 5% of total CO_2 emissions in the world. As a rule of thumb, every 1 ton of cement produced would emit an averagely 0.81 ton of carbon dioxide (Huntzinger and Eatmon, 2009). Thus, it is required to minimize the environmental footprints of the structural designs. One of the solutions to achieve this goal is through Ultra-High Performance Fiber Reinforced Concrete (UHPFRC) technology that provides significant advantages in terms of aesthetic, workability, durability, ductility and sustainability. The UHPFRC technology supports the concept of sustainable construction through efficient use of material and optimization of the structural design. Further, the extremely durable nature of UHPFRC allows the UHPFRC structures to achieve much longer service life and almost negligible maintenance. This directly translates into the saving of cost and raw materials for re-construction (Nematollahi, 2012).

UHPFRC also known as Steel Fiber Reinforced Reactive Powder Concrete (SFR-RPC) is one of the main breakthroughs in concrete technology in the mid 1990's. It was introduced by Richard and Cheyrezy (1994, 1995) with compressive strength over 150 MPa and flexural strength over 30 MPa and remarkable improvement in durability compared to conventional concrete. To date, extensive research and development in the UHPFRC technology have been undertaken by numerous research groups and engineers worldwide. The material characteristics of UHPFRC have been studied in depth and its practical applications have been demonstrated in various countries throughout the world (Voo and Foster, 2009; Fehling *et al*., 2008; Graybeal, 2006; Schmidt *et al*., 2004). Most of the available literature of the UHPFRC structural members were

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focused on the experimental tests of the UHPFRC beams (especially prestressed beams) designed to fail in bending and/or shear (Voo *et al*., 2010; Voo and Foster, 2009; Voo *et al*., 2006). According to the most updated available literature on UHPFRC, there has been no study on the application of UHPFRC in conventional Reinforced Concrete (RC) cantilever retaining walls. Based on the enhanced mechanical properties of UHPFRC, it can offer numerous advantages in terms of aesthetic, workability, durability, ductility and sustainability when used in fabrication of precast concrete cantilever retaining walls.

This study presents the overview of a newly designed precast concrete cantilever retaining wall fabricated from UHPFRC as a sustainable alternative approach compared with the conventional precast RC cantilever retaining wall. Furthermore, the sustainability of the proposed UHPFRC wall is ascertained by comparing the Environmental Impact Calculations (EIC) of both walls with respects to material consumption, CO_2 emission, EE and 100-year Global Warming Potential (GWP).

MATERIALS AND METHODS

Analysis and design of the precast UHPFRC cantilever retaining wall: Figure 1 shows the proposed precast UHPFRC cantilever retaining wall with the dimensions of 2.5 m in height, 2 m in length and 2 m in width which supports a cohesionless horizontal backfill. It is assumed that the soil underneath the wall base and the soil in front of the wall have the same properties which are different from the properties of the backfill. Table 1 presents the soil properties used in this study according to soil characteristics given in Table 1 in BS 8002 (1994). In this study, the precast UHPFRC cantilever retaining wall was analyzed in accordance with BS EN 1997-1:2004 (2004) Eurocode 7 (EC7): Geotechnical design-Part 1: General rules requirements. At first, minimum dimensions of the wall were determined based on the stability and bearing pressure requirements given in EC7. The objective of the stability analysis is to ensure that the UHPFRC wall with the given dimensions is stable in terms of overturning and sliding under the action of the loads corresponding to the ULS (EQU) and the ULS (GEO), respectively. The bearing pressure analysis was also undertaken under the action of the loads corresponding to the ULS (GEO). Subsequently, the structural design of the stem, heel and toe of the wall were undertaken based on the first principles (equilibrium equations) in

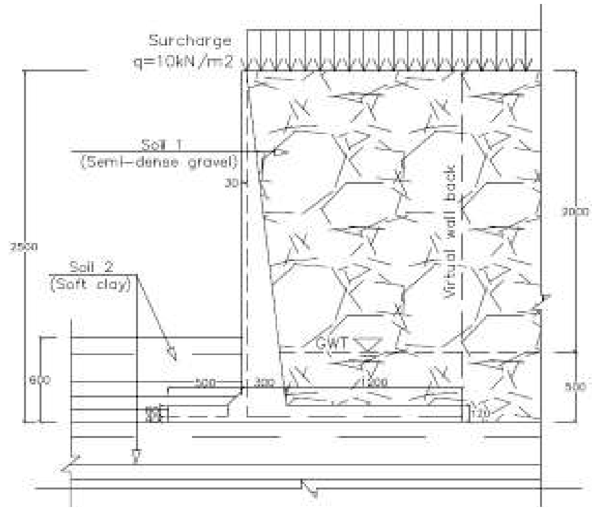

Fig. 1: Soil and GWT conditions used in the analysis of the UHPFRC wall

conjunction with the Japanese Society of Civil Engineers' Recommendations for Design and Construction of Ultra High Strength Fiber Reinforced Concrete Structures (Draft) (JSCE No. 9, 2006).

Drawings of the precast UHPFRC cantilever retaining wall: The proposed precast UHPFRC cantilever retaining wall consists of two integrated thin panels which act as the base panel and the vertical wall panel. The 40 mm thick base panel was strengthened with two 80 mm thick by 100 mm wide steel reinforced stiffeners as shown in Fig. 2. The 30 mm thick vertical wall panel was also strengthened with two steel reinforced stiffeners as shown in Fig. 2 and 3. The action of possible hydrostatic pressure due to the percolating water during rain at the back face of the wall was reduced by arrangement of six weep holes with the diameter of 75 mm in the vertical wall panel as shown in Fig. 2. Besides, by provision of the weep holes, the possibility of seepage throughout the wall is decreased and water is less probable to reach and weaken the soil underneath the wall foundation (Mosley *et al*., 2007). Figure 2 and 3 show the detailed drawings of the precast UHPFRC cantilever retaining wall proposed in this study.

Analysis and design of the conventional precast RC cantilever retaining wall: As the benchmark of this

Table 1: Soil properties used in the analysis of the UHPFRC wall

	Soil type	
Soil properties	Semi dense gravel (soil 1)	Soft clay (soil 2)
Weight density (γ)	17 kN/m^3	17 kN/m^3
Saturated weight density (γ_{sat})	20.5 kN/m^3	17 kN/m^3
Effective cohesion (c')	0 (cohesionless)	22 (cohesive)
Characteristic angle of shearing resistance ($\varnothing'_k$)	30°	35°
Critical state angle of shearing resistance ($\varnothing'_{cv}$)	30°	35°

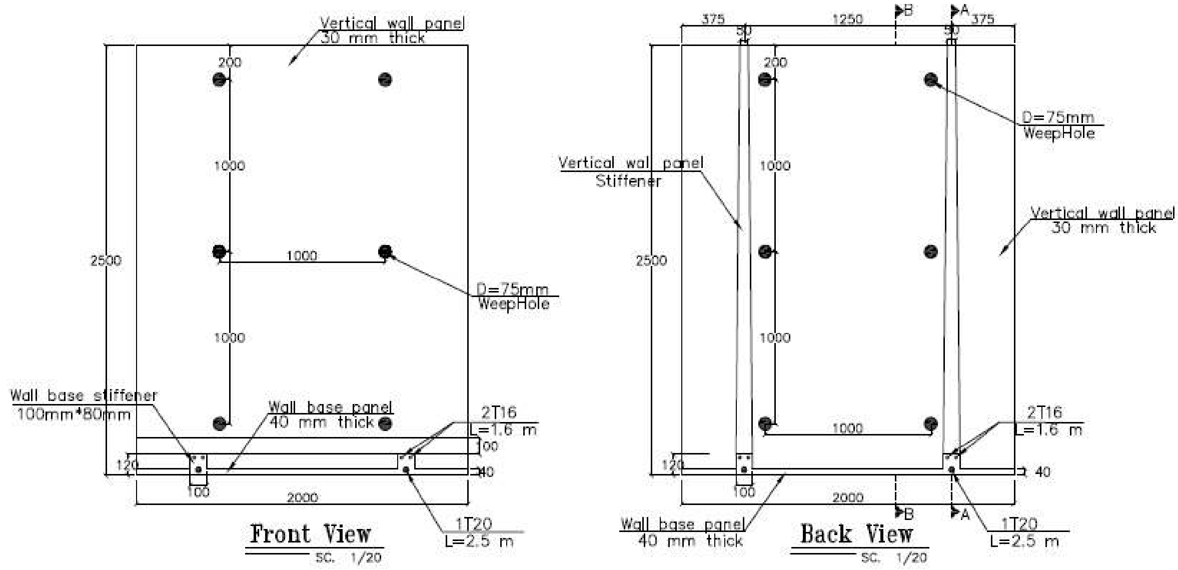

Fig. 2: Front view and back view of the precast UHPFRC cantilever retaining wall

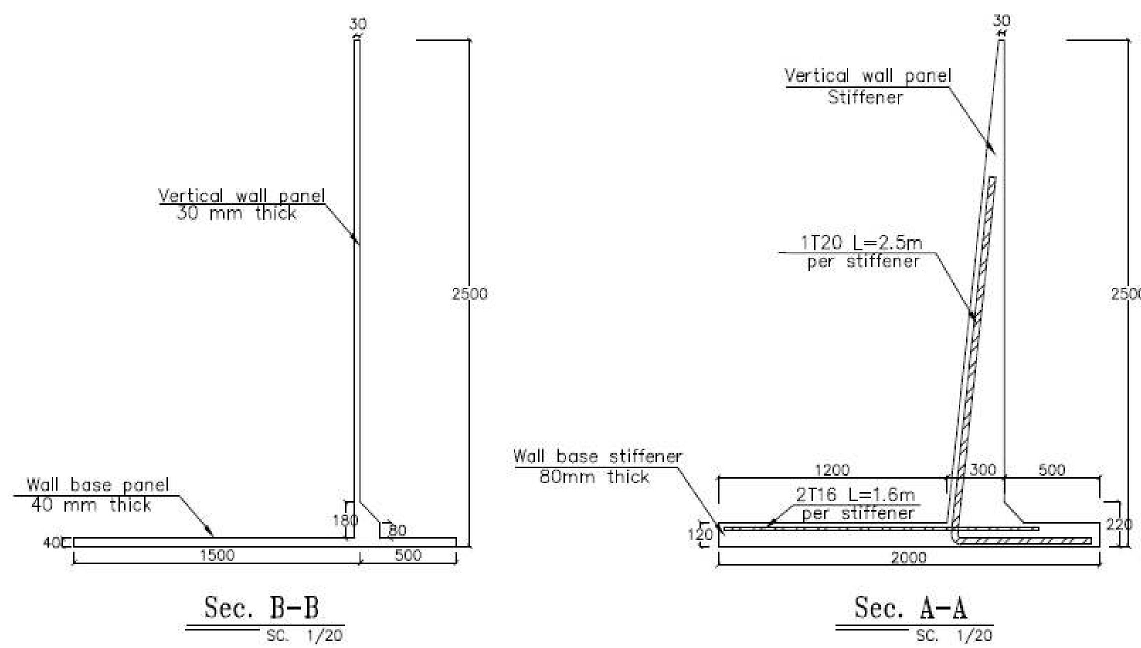

Fig. 3: Sections A-A and B-B of the precast UHPFRC cantilever retaining wall

study a corresponding 2.5 m high conventional RC wall as shown in Fig. 4 was also analyzed based on EC7 requirements with exactly the same soil, Ground Water Table (GWT) and loading conditions as those of the precast UHPFRC wall; whereas the structural design of the conventional RC wall was undertaken based on the requirements given in BS EN 1992-1-1:2004 (2004), Eurocode 2 (EC2): Design of concrete structures- Part 1-1: General rules and rules for buildings. It should be noted that according to Murthy (2003); the minimum thickness of the wall stem and the minimum batter should be equal to 0.3 m and 1:48, respectively. In addition, similar to the UHPFRC wall, the minimum heel length required for development of the conjugate failure planes should be equal to 1.44 m. Thus, the conventional RC wall with the dimensions of 2.5 m in height, 1 m in length and 2.35 m in width was used in this study. Similar to the precast UHPFRC wall, the stability and bearing pressure analysis of the conventional RC wall with the above dimensions were undertaken according to EC7 requirements and all the requirements were met. Subsequently, the structural design of the wall was undertaken in accordance with EC2 requirements. Figure 5 shows the details of the bending reinforcement used in the corresponding conventional precast RC wall.

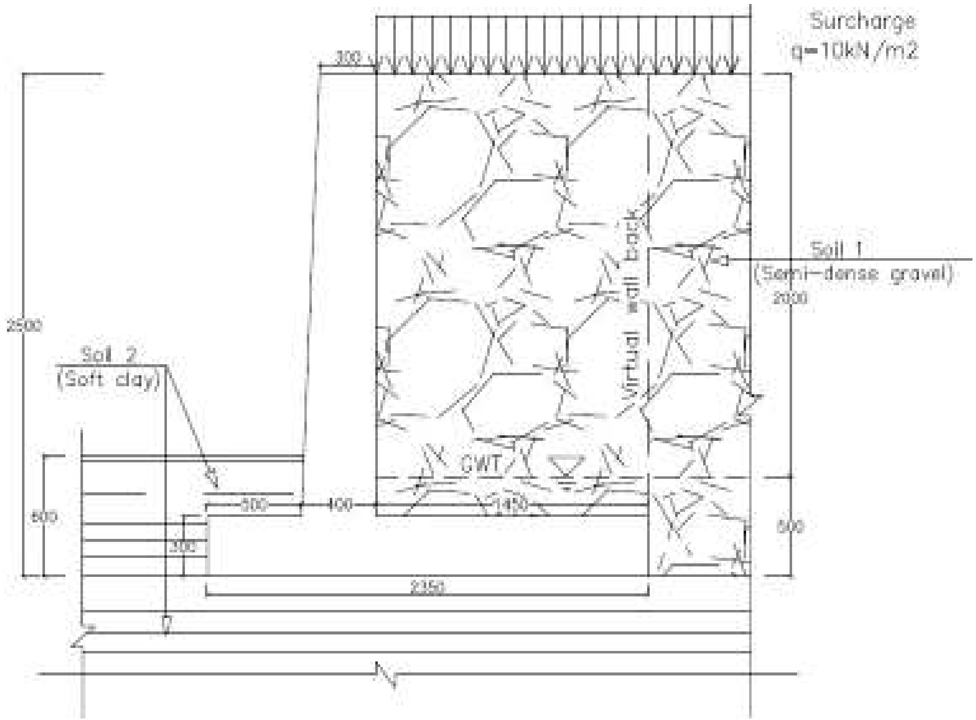

Fig. 4: Dimensions, soil and GWT conditions used in the analysis of the RC wall as the benchmark of this study

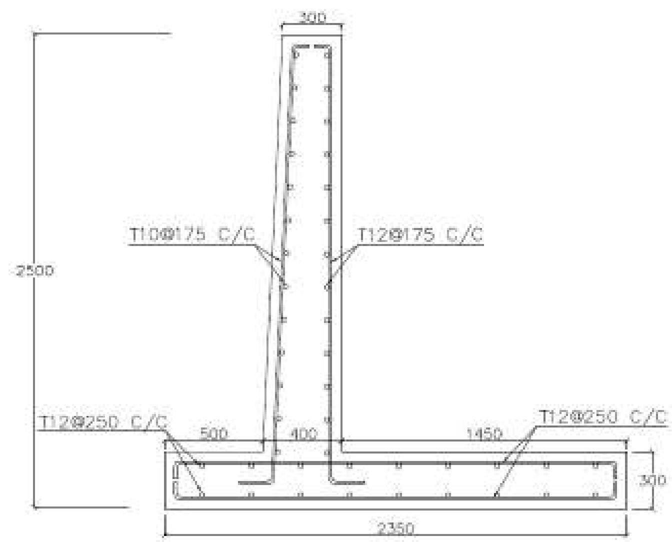

Fig. 5: Details of the bending reinforcement used in the RC wall in STR (ULS)

Table 2: Environmental data used for the EIC

	Units	DURA-UHPFRC (1.5% steel fiber)*	Grade-30 (15% PFA)	Reinforcement
Density	kg/m^3	2350	2350	7840
EE	GJ/m^3	6.814	1.73	185.8
CO_2	kg/m^3	982	297.50	17123
NO_x	kg/m^3	4.860	1.66	55.4
CH_4	kg/m^3	0.760	0.12	30.7
100-year GWP	kg CO_2 eq./m^3	2449	795	34392

*: Environmental values include steel fiber contribution; (Voo and Foster, 2010)

Environmental Impact Calculations (EIC): Environmental Impact Calculations (EIC) of the precast UHPFRC cantilever retaining wall was undertaken to ascertain that the proposed precast UHPFRC cantilever

Table 3: Material quantities and EIC of the two cantilever retaining wall designs

Design method		UHPFRC (1.5% steel fiber) (m^3)	Grade 30 (15% PFA) (m^3)	Reinforcement (kg)	Total
Conventional RC wall	Grade 30 concrete	0	1.47	0	-
	Steel bars	0	0	70.80	-
	Mass of materials used; (kg)	0	3454.50	70.80	3525.3
	EE; (GJ)	0	2.54	1.68	4.2
	CO_2; (kg)	0	437.30	154.30	591.6
	100-yr GWP; (kg CO_2 eq.)	0	1168.70	310.80	1479.5
UHPFRC wall	UHPFRC concrete	0.208	0	0	-
	Steel bars	0	0	14.65	-
	Mass of materials used; (kg)	488.800	0	14.65	503.5
	EE; (GJ)	1.420	0	0.35	1.8
	CO_2; (kg)	204.300	0	31.90	236.2
	100-year GWP; (kg CO_2 eq.)	509.400	0	64.30	573.7

retaining wall as a sustainable alternative solution to the conventional precast RC cantilever retaining walls supports the concept of sustainable construction. The environmental data needed for EIC is presented in Table 2. This table summarizes the values of equivalent CO_2 content, the EE and 100-year GWP of Grade-30 concrete, of DURA®-UHPFRC with 1.5% of steel fibers and of steel reinforcement. The CO_2 emission, EE and GWP values for the production of concrete and steel are obtained from the study of Voo and Foster (2010) and Struble and Godfrey (2004) and are modified as required. GWP is a measure to estimate the contribution of a particular mass of greenhouse gas to global warming over an agreed time intervals (Elrod, 1999). According to Voo and Foster (2010), for simplicity the following formula can be used to measure the 100-year GWP with a unit of kilograms of CO_2 equivalent per kilogram of material (kg CO_2 eq./kg):

$$100\text{-year GWP} = CO_2 + 298\ NO_x + 25\ CH_4 \qquad (1)$$

RESULTS AND DISCUSSION

Table 3 summarizes the material quantities and EIC of the two concrete cantilever retaining wall designs (i.e., the conventional precast RC wall and the newly designed precast UHPFRC wall). The amount of EE, CO_2 emissions and 100-year GWP are derived from multiplying the total amount of each material used in each of the precast wall specimens by their corresponding unit value of the environmental data given in Table 2. It should be pointed out that foundation of the wall and transportation costs are excluded in the calculation of the material quantities of the walls i.e., the material quantities shown in Table 3 are just based on the precast wall specimens. According to this table, the precast UHPFRC wall weighs 503.5 kg/m length of the wall; while, the conventional precast

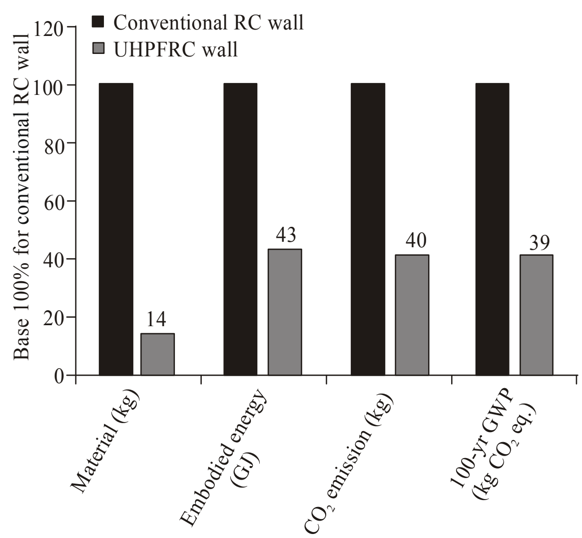

Fig. 6: EIC results of the two cantilever retaining wall designs

RC wall weighs 3525.3 kg/m length of the wall. In other words, the precast UHPFRC wall is seven times lighter than the conventional precast RC wall! In addition, lighter weight of the precast UHPFRC wall will result in a smaller foundation which provides additional savings. Furthermore, due to the lighter structure of the precast UHPFRC wall its standard length is 2 m; whereas the standard length of the conventional precast RC wall is usually 1 m. Hence, the precast UHPFRC wall does not need heavy lifting and installation machineries compared to the conventional precast RC wall which leads to a reduction in transportation costs and installation time. With respect to reinforcement, the precast UHPFRC wall eliminates the use of secondary reinforcements and crack control bars needed in the stem and the base of the conventional precast RC wall. In addition, it also removes the need of reinforcement required in the compression face of the wall stem. Thus, the total weight of the reinforcement needed is many times less than the conventional precast RC wall.

Figure 6 shows a comparison of the EIC results of the two cantilever retaining wall designs based on 100% for the conventional RC wall. As can be seen in this figure, regarding material consumption, the proposed precast UHPFRC wall consumed 86% less material than the conventional precast RC wall. Further, with regards to environmental impact, the precast UHPFRC wall has 57% less Embodied Energy (EE) and 60% less CO_2 emissions compared with the precast RC wall. In addition, with respect to the 100-year GWP, the precast UHPFRC wall offers a decrease of 61% over that of the conventional precast RC wall. It is necessary to point out that only the savings at the stage of the wall design have been considered in this study. Considering the lighter weight of the precast UHPFRC wall will result in a smaller foundation and lower transportation costs, thereby additional savings will be obtained.

CONCLUSION

This study evaluates the environmental impacts of a newly designed precast UHPFRC cantilever retaining wall. According to the results of EIC, in terms of raw material consumption the precast UHPFRC wall gives immediate saving of 86% compared against the conventional precast RC wall. In other words, the precast UHPFRC wall is seven times lighter than the conventional precast RC wall. In addition, in term of environmental impact indexes the precast UHPFRC wall is confirmed to be much more sustainable as its EE and CO_2 emission values are approximately 57 and 60% less than those of the conventional precast RC wall, respectively. Moreover, in terms of the 100-year GWP, a decrease of 61% is achieved by using the precast UHPFRC wall over that of the conventional precast RC wall. It is necessary to indicate that these savings are only obtained in the stage of the wall design and further savings will be achieved if the smaller foundation and reduced transportation costs are considered resulted by the lighter weight of the precast UHPFRC wall. In summary, the precast UHPFRC cantilever retaining wall proposed in this study is a green structural member that supports the concepts of sustainable construction which can be used as an alternative sustainable approach compared to the conventional precast RC cantilever retaining walls.

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