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GHG mitigation of railway concrete products using eco-concrete and surface protection agent

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HIGHLIGHTS

- GHG saving effect of the eco-concrete in railway was calculated with LCA analysis.
- Concrete deterioration preventive agent were applied and physical performance tested.
- Life cycle GHG reduction by eco-concrete and anti-deterioration agent was calculated.

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ABSTRACT

This study investigated the life cycle greenhouse gases (GHG) mitigation effect of railway infrastructure through the application of an eco-concrete, using ground granulated blast furnace (GGBF) slag and electric arc furnace (EAF) slag as alternative materials in railway sleeper, and a concrete surface protection agent in railway track. A simplified life cycle assessment method was applied to compare GHG emissions and an instrumental analysis as well as a physical performance test were carried out to identify the protection mechanism between the agent and concrete along with field tests. From this study, it was found that two different approaches might contribute substantially to mitigate GHG emissions from railway infrastructure. The surface protection agent with an anti-deterioration function showed high possibility of increasing lifespan of the concrete structure and the use of alternative materials, such as furnace slag, reduced the concrete consumption by more than 20% (w/w). It was estimated that the potential GHG mitigation effects from the surface protection agent and eco-concrete technology applied to a railway concrete track were at least 27 ton CO_2 eq. per km a year and 11.1 kg of CO_2 eq. per 1 sleeper, respectively.

1. Introduction

Buildings and construction account for about 30% of global energy-related GHG emissions [1]. In order to lower greenhouse gas (GHG) emissions and improve energy efficiency in buildings and construction, eco-design using life cycle assessment (LCA) is widely employed considering its life cycle environmental aspects [2–5]. Since concrete has been used the most widely as a construction material in roads, buildings, bridges and other infrastructures, it is important to evaluate the environmental impacts of this material, considering the GHG emissions and the impacts on climate change it generates [6,7]. Concrete, the most consumed material by humans after water, has recently been under scrutiny for the environmental impacts associated with its production [8].

Steel slag is widely used as a supplementary cementitious material in order to reduce GHG emissions and increase material efficiency throughout the cement industry [9]. Ferreira analyzed technical requirements and environmental impacts derived from the application of electric arc furnace (EAF) slag as a pavement aggregate. It has been revealed that EAF slag shows excellent mechanical properties that improve the skid resistance of the pavement and reduce the risk of aquaplaning due to higher permeability [10]. It has been also found that lower environmental impacts can be expected compared to the case with natural aggregate from the LCA analysis. Balaguera investigated potential environmental benefits for the use of alternatives in road construction with the LCA concept [11].

Another solution of lowering GHG emissions for buildings and construction is to extend their lifespan as much as possible by

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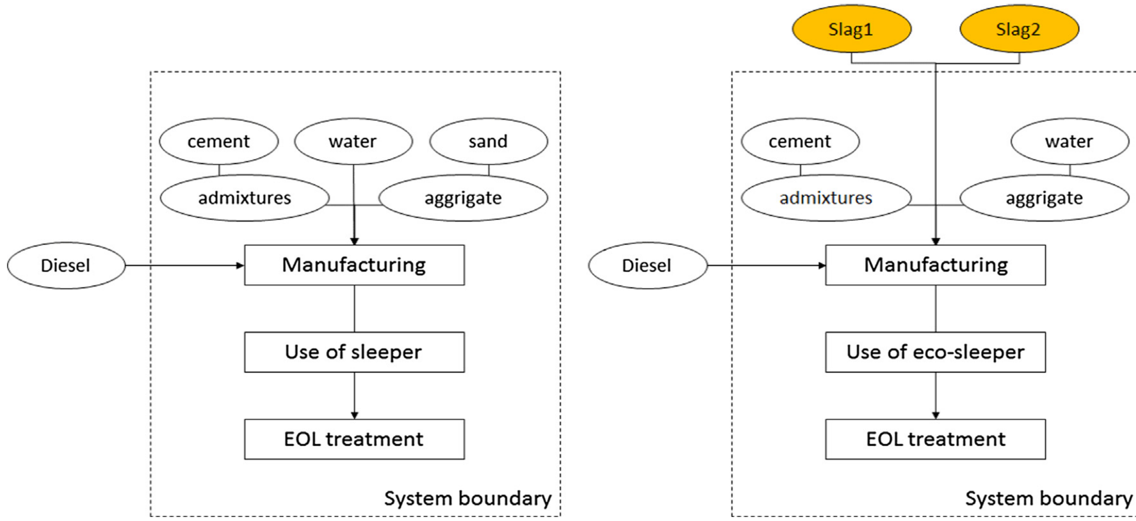


Fig. 1. System boundary between eco-sleeper (R) and conventional sleeper (L).

preventing deterioration of the concrete structure. Pan comprehensively reviewed concrete surface treatment studies and noted the advantages and drawbacks of each treatment [12,13]. Wang proposed a life-cycle design (LCD) method, combining traditional design with green design, for concrete structures to promote the long-term performance of a structure [14].

Table 1
Materials and energy input for manufacturing a sleeper.

Input	Unit	Sleeper	Eco-sleeper
Cement	Kg	45.32	34.81
GGBF	Kg	–	17.94
Water	Kg	13.6	13.7
Sand	Kg	72.2	
EFA	Kg	–	104.3
Aggregate	Kg	118.1	102.0
Admixtures	Kg	0.815	0.373
Total	Kg	250.035	273.123
Diesel	L	2	2

Railway infrastructures demand massive materials for construction and have long lifespan so that most of the GHGs are generated at the construction stage, whereas rolling stock consumes a large amount of electricity during its operation stage [15]. From several LCA studies regarding railway infrastructure, it has been also found that concrete is one of the main contributors of GHG emissions [16–18]. In order to decrease GHG emissions released from the use of concrete in railway infrastructure, it is very important to consider an application of the eco-concrete using supplementary materials and a deterioration protection agent which is helpful for lengthening its life span. However, most previous studies to apply furnace slags in the railway industry have focused on analyzing the physical performance without the consideration of environmental impacts [19–21]. The aim of this study was to investigate GHG mitigation effects using a LCA methodology from the application of furnace slags and a concrete surface protection agent in railway concrete structures.

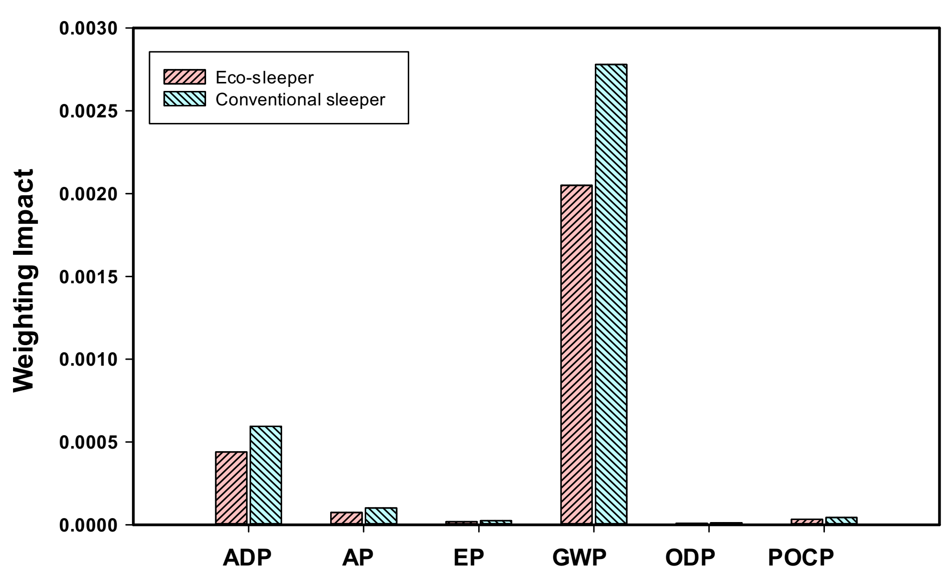


Fig. 2. Life cycle impact assessment between conventional sleeper and eco-sleeper (ADP: abiotic resource depletion potential, AP: acidification potential, EP: eutrophication potential, GWP: global warming potential, ODP: ozone layer depletion potential, POCP: photochemical ozone creation potential).

Fig. 3. Concrete slab track, before (L) and after (R).

2. GHG mitigation effect of the eco-sleeper

The physical performance of the eco-sleeper applied in this study was evaluated by Ko et al. [19]. In this study, a LCA analysis was implemented for the investigation of the GHG mitigation effect from the application of the furnace slags in railway sleeper according to the requirements of ISO 14040 and 14044 standards [22,23], by means of its four major stages: goal and scope definition; life cycle inventory (LCI); life cycle impact assessment (LCIA); and interpretation.

2.1. Goal and scope definition

The goal of this study is to compare the environmental performances, focusing on the GHG emissions, of two types of sleepers (conventional sleeper and eco-sleeper adopted furnace slags as an alternative material). The function of a sleeper is to maintain a certain distance between rails and transmit the load on the rails to the subbase through the ballast. One sleeper was defined as a functional unit. It was assumed that the service life of the sleeper was 60 years [24]. Transportation and maintenance data during service life, which would be equally applicable to both products, were not included. 0.1% (w/w) of waste concrete would be buried while 99.9% (w/w) would be recycled according to the waste generation and disposal database of the Korea Environment Agency [25].

Fig. 1 shows the system boundary between the eco-sleeper and the conventional sleeper for the LCA. Ground granulated blast furnace (GGBF) and electric arc furnace (EAF) oxidizing slag in an eco-sleeper were excluded in this study because they are recycled materials generated from the steel industry.

2.2. Data collection

As listed in Table 1, the amount of materials and fuel consumptions used for the production of both sleepers were collected from a representative railway sleeper manufacturing site in South Korea. In order to implement the LCA for the selected product, the PASS (Product Assessment for Sustainable Solutions) program [26] and built-in database were used while an eco-invent database was used only for a natural sand.

2.3. Impact assessment and interpretation

The life cycle impact assessment (LCIA) results were calculated using the environmental product declaration (EPD) method, developed by Korean Environment Agency, embedded in the PASS program at the midpoint level. As shown in Fig. 2 six midpoint categories were assessed. The Global Warming Potential (GWP) of an eco-sleeper was remarkably less (11.1 kg of CO_2 eq., or 78% of total GWP) than a conventional sleeper. These results were caused by the reduction of cement consumption due to the use of slags.

3. Effect of the surface protection agent on the extension of lifespan

3.1. Materials and field test

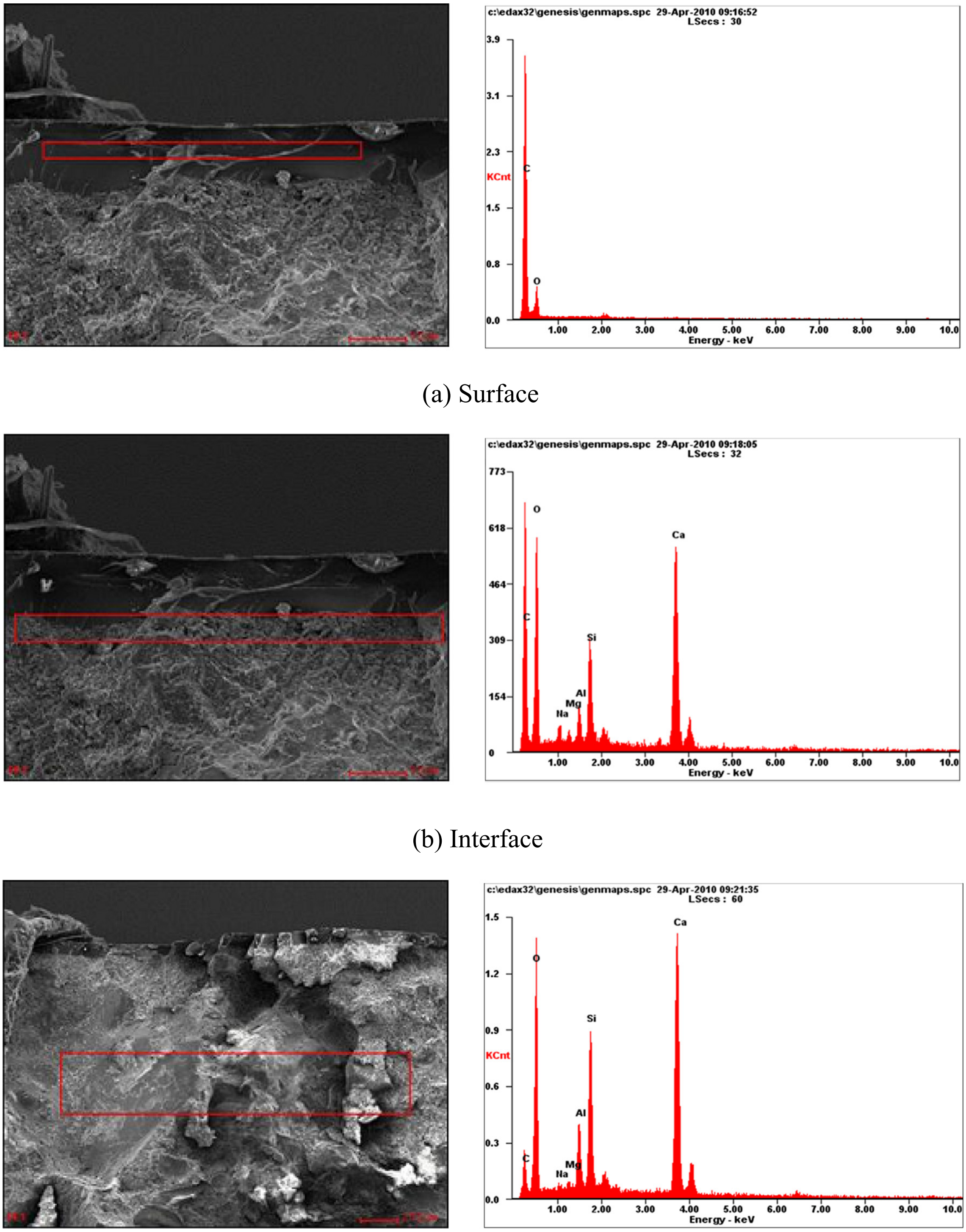
It has been assessed that concrete structures quickly deteriorate, resulting in reduced structural performance, due to the effect of chloride ions and water, which lead to corrosion of the reinforcing steel structure. Several approaches provide additional protection for materials against degradation, including (1) metal, epoxy resin, and polymer coatings for steel rebar; (2) corrosion inhibitors; (3) electrochemical treatment, which is usually used in concrete re-alkalization; and (4) concrete surface treatment [12,13]. In this study, a liquid polyester-based concrete surface protection agent, which is able to penetrate the concrete and form a coated layer on the surface, was coated on a concrete railway track on the South-East line in Busan, South Korea, as shown in Fig. 3. Visual observation revealed greatly improved resistance to moisture and contamination, lasting for years.

3.2. Instrumental analysis

Samples were prepared to analyze the performance of the surface protection agent applied in the field and the level of penetration into the concrete.

3.2.1. Scanning electron microscopy (SEM) and energy dispersive X-ray spectrometry (EDX)

The property of the internal concrete penetration and surface coating was investigated using a scanning electron microscope (SEM FEG Quanta 400 from FEI, USA; using an accelerating voltage of 15 keV and a current intensity of 1 nA) connected to an X-ray spectrometer (Oxford INCA system). Fig. 4 describes the surface



(c) Inside

Fig. 4. Results of SEM and EDX analysis for the sample after the surface treatment with the anti-deterioration agent.

(a), interface (b), and interior (c) of the sample coated with the anti-deterioration agent detected using SEM and EDX. Compared with Fig. 4(c), the strong carbon peaks in Fig. 4(a) and (b) confirm the coating and penetration of the anti-deterioration agent into the concrete.

3.2.2. FT-IR spectroscopy

A Nicolet iS10 (Thermo Fisher Scientific Inc., USA) equipped with a deuterated triglycine sulfate (DTGS) detector and controlled with OMNIC software was used to obtain FT-IR spectra of the sample before and after the surface treatment with the anti-aging agent of a polyester based carboxyl compound. As depicted in

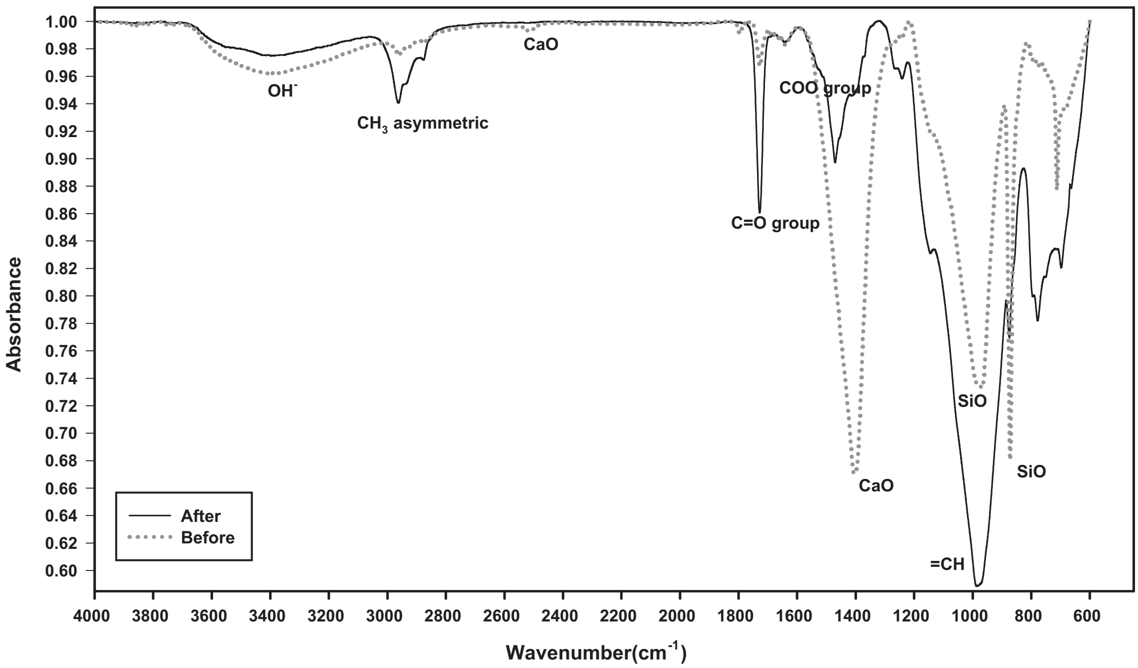


Fig. 5. FT-IR spectroscopy analysis before and after the surface treatment agent.

Fig. 5, a strong peak was identified at 1400 cm^{-1} (ascribed to Ca—O bonding) and 1000 cm^{-1} (assigned to Si—O bonding), and this peak then disappeared or diminished after surface treatment from the band of the carboxyl compound (appearing at 1700 cm^{-1}) and C—H band (absorbed at 1000 cm^{-1}). These IR absorption spectra were well matched with the results of Horgnies et al. [27] who studied the adhesion properties of concrete surfaces using FT-IR spectroscopy under different interlinked conditions at the interface.

3.2.3. XPS measurements

Samples were used for the X-ray photoelectron spectra (XPS) measurements with a ThermoVG SIGMA PROBE X-ray photoelectron spectrometer. Fig. 6 depicts the results of the XPS analysis with bonding energy transitions on the surface of the sample with carbon and calcium elements before and after chemical agent treatment. It was found that the relative peak intensity of C 1s increased, while Ca 2p decreased and shifted after the sample was coated. From the peak shift and lower intensity of the Ca 2P, it is supposed that the Ca element on the surface is covered by the anti-deterioration agent and becomes chemically combined with the organic agent.

3.3. Physical performance of the concrete surface protection

The physical performance of the agent was tested in accordance with KS F 4936 [28]. KS F 4936 specifies the test methods related to the blocking performance against the penetration of chloride, carbon dioxide, and other harmful substances into the concrete from outside for coating materials forming layer on the surface of concrete for the purpose of protecting the concrete with several related standards for each test item. The appearance after coating, neutralization depth, resistance to penetration of chloride ions and moisture permeability, resistance to water permeability, bond strength, and anti-crack performance were observed. Table 2 summarizes the results of the protective test for the sample after the surface protection agent was applied. The coated sample showed a good performance that satisfied all requirements of KS F 4936 related to coating materials to protect concrete.

In addition, the agent was also tested according to the KS F 4930 specifying requirements for the liquid-type water repellent agent that forms a layer to prevent absorption and the inhibition of the penetration of water and chloride ions (Cl^-) from outside [29]. Table 3 lists test items and results. As identified previously by the SEM analysis, the penetration depth of the agent into the concrete was about 4 mm. The SEM analysis also confirmed excellent resistance to chloride and water, the main causes of concrete neutralization.

3.4. GHG mitigation effect from the surface protection agent application

To estimate the GHG mitigation effect from the use of the surface protection agent, slab track (standard gauge double track, 0.35 (h) × 4.2 (w) × 1000 m (h) dimension) was taken. It was investigated that 1,722 tons of cement was used for 1 km of slab track construction from the field data collection [30]. By applying the emission factor of a cement, 0.944 kg CO_2 eq. for 1 kg cement [31], it was converted into 1625 ton CO_2 eq. per 1 km of slab track for 60 years of lifespan. From the field test in this study, it was also found that 1260 L of the agent was required to coat 1 km of the track, which is equivalent to the amount of 2620 kg CO_2 eq. by using the emission factor of 2.08 kg CO_2 eq./1 L of the agent calculated from the simplified LCA. Due to lack of information related to the manufacturing process of the agent, only material inputs (polyester and gasoline) was considered. As a result, it was estimated that 27 ton CO_2 eq. per km might be saved by the lifespan extension of one year using the surface protection agent.

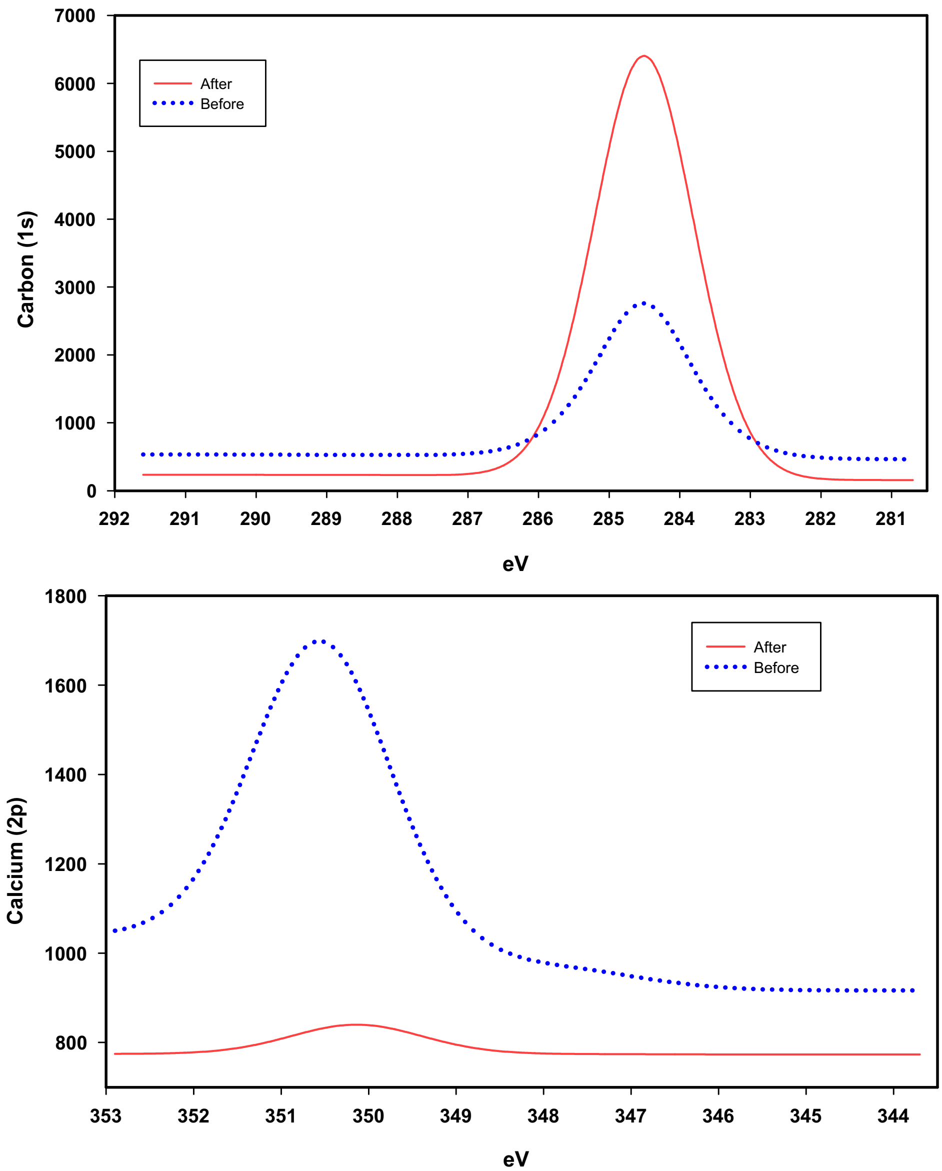


Fig. 6. XPS analysis before and after the surface protection agent.

Table 2
Performance requirements and results (KS F 4936:2008).

Item		Standard value	Test result
Surface condition after coating	After standard curing After accelerated weather test After repeated low- and high-temperature resistance test After alkali-resistance test After salt water test	No wrinkles, pinholes, transform or exfoliation	Not detected
Depth of neutralization (mm)		1.0 or less	0.2
Chloride ion-resistance		1000 or less	201
Permeability (g/m^2/day)		50.0 or less	3.0
Permeability resistance		Not detected	Not detected

4. Conclusions

To achieve greener railway infrastructure, in general, several sustainable options through material choice could be available; cement replacement materials, use of reclaimed, recycled and site-won materials, local sourcing strategy and durability increase of material and infrastructure. This study suggested two options, including the eco-sleeper as one of the saving technologies of concrete use and the concrete surface protection agent as one of the durability increase technologies, for greener railway infrastructure. It was confirmed that the suggested two options had substantial GHG mitigation effects through a LCA application. In addition, the physical performances of concrete surface production agent were evaluated by field test. Allowing for the intrinsic characteristic of railway industry, where it is very difficult to adopt directly the technologies that have not been verified and proved fully in the field. Thus, the greener options should be considered simultaneously with further experiments related to reliability and economic assessment in the future.

Table 3
Performance requirements and results of the surface treatment for concrete (KS F 4930:2012).

Item		Unit	Standard value	Test result
Depth of penetration		mm	2.0 or more	4.3
Absorption resistance	Standard condition	–	Water absorption coefficient of 0.50 or less	0.06
	After alkali-resistance test	–		0.06
	After repeated low- and high-temperature resistance test	–		0.05
	After accelerated weathering test	–		0.07
Permeability resistance		–	Water permeability ratio of 0.10 or less	0.09
Resistance to chloride ion penetration		mm	3.0 or less	Not detected
Elution resistance	Smell and taste	–	There should be no abnormalities	No smell and taste
	Turbidity	degree	2 or less	0.1
	Chromaticity	degree	5 or less	0.1
	Presence of heavy metal (Pb)	mg/L	0.1 or less	Not detected
	Potassium permanganate consumption	mg/L	10 or less	2.0
	pH	–	5.8–8.6	8.2
	Phenol	mg/L	0.005 or less	Not detected
	Evaporation residue	mg/L	30 or less	1.2
	Weight loss from residual chlorine	mg/L	0.2 or less	0.1
Flash point		°C	No flame shall occur below 80 °C	over 85

Conflict of interest

We certify that there is no conflict of interest with any financial organization regarding the material discussed in the manuscript.

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