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Ontology Framework for Sustainability Evaluation of Cement–Steel-Slag-Stabilized Soft Soil Based on Life Cycle Assessment Approach

Chunyang Yu [1], Jia Yuan [1], Chunyi Cui [1,*], Jiuye Zhao [1], Fang Liu [2] and Gang Li [2]

[1] Department of Transportation Engineering, Dalian Maritime University, Dalian 116026, China; yuchunyang@dlmu.edu.cn (C.Y.); yuanjia@dlmu.edu.cn (J.Y.); zhaojiuye@dlmu.edu.cn (J.Z.)
[2] Shaanxi Key Laboratory of Safety and Durability of Concrete Structures, Xijing University, Xi'an 710123, China; liufang_winter@163.com (F.L.); t_bag945@126.com (G.L.)
* Correspondence: cuichunyi@dlmu.edu.cn

Abstract: Steel slag has become a promising supplementary cementitious material for soft soil stabilization. However, there is a lack of research on the integrated assessment of cement–steel-slag-stabilized soft soils (SCSs) from the performance, environmental, and economic perspectives. In this study, an ontology framework for the sustainable evaluation of SCSs was developed based on the life cycle assessment (LCA) approach, which combined a knowledge base with semantic web rules to achieve an automated decision design for soft soil stabilization, considering comprehensive benefits. The ontology framework was applied to a marine soft soil stabilization case to verify its scientificity and practicability and to evaluate the influence of the fineness, carbonation degree, and substitution ratio of steel slag on the sustainability of SCSs. The results show that, when compared to pure-cement-stabilized soil (S-C), using 10% and 20% of fine steel slag carbonated for 18 h (FSS-C-18h) as cement substitutes can significantly reduce carbon emissions and costs while achieving a similar strength performance as S-C, demonstrating the feasibility of steel slag as a sustainable supplementary cementitious material for soft soil stabilization.

Keywords: ontology; steel slag; stabilized soils; foundation; LCA; sustainability evaluation

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1. Introduction

Soft soils are widely distributed in coastal areas and are characterized by a high natural water content, low bearing capacity, and high compressibility, and cannot be used directly in engineering [1]. However, the treatment of the soft soil foundation is a very challenging task, which requires certain methods such as preloading, chemical stabilization, and electro-osmosis [2,3]. The chemical stabilization method is widely used to achieve the stabilization of soft soil by mixing some cementitious materials (such as cement, lime, water glass, ion-exchange-class, and polymer-class stabilized materials, etc.) into the soft soil [4–6].

Cement is widely used in the field of soft soil stabilization due to its wide range of sources and stable properties. However, cement has problems such as high energy consumption, high carbon emission, consumption of non-renewable resources, and environmental pollution [7,8]. Replacing cement with low-carbon supplementary cementitious materials (SCMs) such as steel slag, fly ash, and silica fume is considered as the most promising strategy for sustainable soft soil stabilization design [9–11].

Steel slag is the solid waste the metallurgical industry produces, accounting for about 12–15% of steel output [12,13]. Steel slag is a potential SCM due to its similar composition to cement [14,15]. The low reactivity and poor volume stability of steel slag can be improved by grinding and carbonation [16,17]. Most of the existing studies on the partial replacement of cement by steel slag for soft soil stabilization have focused on the effect of steel slag on the mechanical properties of stabilized soil [18,19]. However, there is a lack of scientific quantitative research on the environmental and economic impact of cement–steel-slag-stabilized soils (SCSs).

Life cycle assessment (LCA) is a scientific method to qualitatively and quantitatively assess the potential environmental impact of a product or process during its life cycle [20,21], and LCA is considered one of the essential tools for sustainability assessment. Ghasemi et al. [22] performed the LCA study to compare the environmental impact using slurry and wet carbonation processes for converter slag and found that the net avoided global warming potential (GWP) of the slurry and wet routes were 525.56 and 426.67 $kgCO_2eq/MWh$, respectively. Li et al. [23] evaluated the environmental impact of steel slag aggregates and steel slag blocks. The GWP results showed that steel slag blocks could achieve negative carbon emissions. However, LCA involves complex logical relationships between products, activities, and the environment, the results of which are often difficult to understand and to use to share inventory information between different disciplines [24].

Ontology can standardize concepts, terms, and their relationships, provide methodologies for building knowledge frameworks, and is widely used for information retrieval, integration, decision making, and knowledge sharing between different domains by combining knowledge terms and predefined rules [25,26]. Zhang et al. [27] proposed an ontology-based semantic representation method for the product life cycle, which implemented a formalized and shared product life cycle design. Hou et al. [28] developed the concrete structures design ontology with embodied energy and carbon as sustainable evaluation indices. Meng et al. [29] proposed a multi-objective design method for an energy pile system based on ontology from the perspective of technology, economy, and sustainability. Based on the Monte Carlo simulation approach, Cui et al. [30] established a comprehensive seismic risk assessment ontology framework for the subway station. Ontology has obvious advantages in solving multi-domain, multi-objective problems due to its shareability, interoperability, and reusability. However, little research has been carried out to develop ontology frameworks for soft soil stabilization.

This study intends to propose a sustainable evaluation framework for SCSs based on LCA and ontology. The framework takes unconfined compressive strength (UCS), GWP, and cost as indicators, and conducts a multi-objective decision-making study on stabilized soils by combining a knowledge base with semantic web rules, with a view to obtaining a design method for soft soil stabilization with optimal overall benefits. This paper is organized as follows: In Section 2, the LCA method is applied to quantify the GWP and costs at each stage of the life cycle and to propose sustainable environmental and economic indicators. Section 3 presents the development of the ontology framework for the evaluation of stabilized soils (OntoESS). Section 4 conducts a case study of marine soft soil stabilization to verify the practicality of the OntoESS framework and to investigate the effects of steel slag fineness, carbonation degree, and substitution ratio on the sustainability of stabilized soils and to compare it with the sustainability of pure-cement-stabilized soils (S-C). The main conclusions and next steps of this study are presented in Section 5.

2. Life Cycle Assessment Methodology

2.1. Goal and Scope Definition

The goal of the life cycle assessment (LCA) in this study is to assess the potential environmental and economic impacts of SCSs and compare them with pure-cement-stabilized soil (S-C). The global warming potential (GWP, measured in terms of carbon dioxide equivalent), which is most important to industries, is selected as the life cycle environmental indicator [31]. The GWP is the mass of CO_2 for whom the greenhouse effect of various greenhouse gases corresponds to the same effect in a 100-year time frame. CO_2 is used as the reference gas because it has the greatest impact on global warming [32].

The functional unit is defined as “the cement–steel slag stabilizer required to stabilize 1 m^3 soft soils”. The system research boundary belongs to the “cradle to gate” as shown in Figure 1, including the production of raw materials, the transportation of raw materials to the factory, and the stabilizer preparation process (grinding and carbonation), without considering the transportation of stabilizers to the construction site and the compaction process with soft soil, as the carbon emissions of SCSs and S-C at these stages can be considered to be similar. The input of the LCA includes energy (diesel, coal, and electricity) and raw materials (cement and steel slag). The output of the LCA only considers greenhouse gases represented by CO_2.

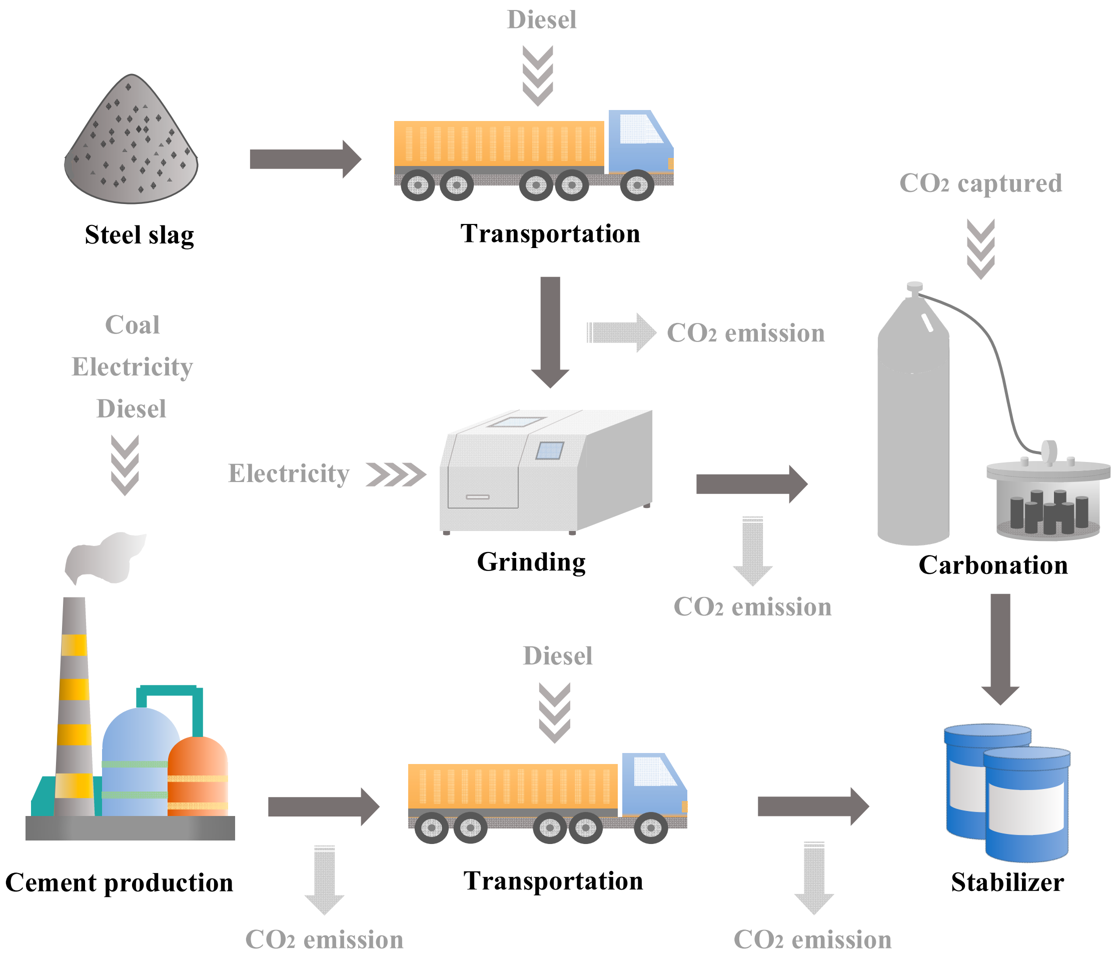


Figure 1. System boundary for cement–steel slag stabilizer production (cradle to gate).

2.2. Life Cycle Inventory

To assess carbon emissions at all stages within the system boundary, it is necessary to collect all input inventory data. In this study, the raw materials required and the measured energy consumption are used as the basis for the life cycle inventory analysis, and the carbon emission factors are taken from the inventory of carbon and energy (ICE) and from relevant literature [33,34].

Steel slag is mostly disposed of in landfills as a waste product from the metallurgical industry [35], and, in most cases, is considered as unintended residual waste. Therefore, according to the recommendations of ISO 14040 [36], the environmental impact of steel slag production is not allocated. The electricity consumption in the preparation of the stabilizer comes from the grinding of the steel slag, which generates carbon emissions that should be converted using the average carbon emission factors for China's regional power grids published by the National Development and Reform Commission [34]. The carbonation of steel slag is a self-heating reaction without an external heat source, so there is no energy consumption. The carbon emission factors of cement production, electricity consumption, and heavy diesel truck transportation are shown in Table 1.

Table 1. Carbon emission factors of materials, transportation, and electricity.

Cement Production ($CO_{2\text{-}mf}$)	Electricity ($CO_{2\text{-}ef}$)	Transportation ($CO_{2\text{-}tf}$)
(kgCO_2-eq/t)	(kgCO_2-eq/kWh)	(kgCO_2-eq/t-km)
735	0.7769	0.162

2.3. Life Cycle Environmental Impact Assessment

According to the system boundary, carbon emissions during the life cycle include the three stages of raw material production, raw material transportation, and stabilizer preparation. Moreover, the resource utilization of steel slag can avoid carbon emissions caused by landfills, herein referred to as the transportation of steel slag to landfills. Total carbon emissions can be calculated based on Equation (1):

$$CO_2 = CO_{2-m} + CO_{2-t} + CO_{2-p} - CO_{2-a} \quad (1)$$

where CO_{2-m} is the carbon emissions of the raw material production process (kgCO_2-eq), CO_{2-t} is the carbon emissions of the raw material transportation process, CO_{2-p} is the carbon emissions of the stabilizer preparation process, and CO_{2-a} is the carbon emissions of avoiding landfill.

Carbon emissions from material production only consider cement, calculated by Equation (2):

$$CO_{2-m} = W_c \times CO_{2-\mathrm{mf}} \quad (2)$$

where W_c is the weight of cement (t), and $CO_{2-\mathrm{mf}}$ is the carbon emission factor for cement production (kgCO_2-eq/t); see Table 1 for details.

CO_2 emissions from material transportation can be obtained by Equation (3):

$$CO_{2-t} = W_c \times D_c \times CO_{2-tf} + W_s \times D_s \times CO_{2-tf} \quad (3)$$

where D_c and D_s represent the distance from the cement and steel slag to the plant (km), respectively. $CO_{2-\mathrm{tf}}$ represents the carbon emissions of fuel consumed when transporting each unit of the ith material in 1 km (kgCO_2-eq/t-km); see Table 1 for details.

Carbon emissions from the stabilizer preparation include the electricity consumption for the grinding of the steel slag, and the CO_2 *uptake* during carbonation, as shown in Equation (4):

$$CO_{2-p} = E_g \times CO_{2-ef} - W_s \times CO_2\ uptake \times 1000 \quad (4)$$

where E_g is the electricity consumption per hour (kWh) for the grinding processes, and CO_{2-ef} is the electricity carbon emission factor (kgCO_2-eq/kWh); see Table 1 for details. W_s is the weight of the steel slag (t). CO_2 *uptake* (%) represents the ratio of CO_2 absorption to the amount of steel slag, measured by the rate of mass weight gain of the steel slag after carbonation. CO_2 *uptake* can be calculated by Equation (5):

$$CO_2\ uptake = \frac{m_{s-carbonated} - m_{s-initial}}{m_{s-initial}} \times 100\% \quad (5)$$

where $m_{s\text{-}initial}$ *is* the weight of the dried steel slag before the carbonation reaction, and $m_{s\text{-}carbonated}$ is the weight of the dried carbonated steel slag.

Carbon emissions of steel slag from avoiding landfill can be calculated based on Equation (6):

$$CO_{2-a} = W_s \times D_a \times CO_{2-tf} \quad (6)$$

where D_a represent the distance from the steel slag to the landfill (km).

2.4. Life Cycle Economic Impact Assessment

The production cost within the system boundary is used as the life cycle economic indicator, including raw material, transportation, stabilizer preparation, and avoiding landfill costs, which are converted into US dollars based on market prices and exchange rates during the study period [37]. (In January 2023, the median exchange rate of the Chinese RMB in the interbank foreign exchange market was US $1 to RMB 6.7626.) Raw material costs include the purchase of cement and steel slag. Transportation costs include the transportation of cement and steel slag to the plant. The cost of stabilizer preparation is the electricity consumption for the steel-slag-grinding process. The cost of avoiding landfill only considers the transportation of steel slag to the landfill. Unit prices of materials, transportation, and electricity are shown in Table 2. Labor and mechanical costs are not considered in this study.

Table 2. The unit price of materials, transportation, and electricity.

Cement ($Cost_{mc}$)	Steel Slag ($Cost_{ms}$)	Transportation ($Cost_{tf}$)	Electricity ($Cost_{ef}$)
(USD/t)	(USD/t)	(USD/t-km)	(USD/kWh)
67.8	10	0.14	0.145

The total cost can be obtained by Equation (7):

$$Cost = Cost_m + _t + Cost_p - Cost_a \quad (7)$$

where $Cost_m$ is the cost of raw materials, $Cost_p$ is the cost of stabilizer preparation, $Cost_t$ is the cost of material transportation, and $Cost_a$ is the cost of avoiding landfill.

The raw material cost can be expressed as Equation (8):

$$Cost_m = W_c \times Cost_{mc} + W_s \times Cost_{ms} \quad (8)$$

where W_c and W_c represent the weight of the cement and steel slag (t), respectively. $Cost_{mc}$ and $Cost_{ms}$ are the price per ton of cement and steel slag (USD/t), respectively; see Table 2 for details.

The material transportation cost is calculated by Equation (9):

$$Cost_t = W_c \times D_c \times Cost_{tf} + W_s \times D_s \times Cost_{tf} \quad (9)$$

where D_c and D_s represent the distance from the cement and steel slag to the plant (km), respectively. $Cost_{tf}$ represents the cost of fuel consumed when transporting each unit of the ith material in 1 km (USD/t-km); see Table 2 for details.

The stabilizer preparation cost is calculated by Equation (10):

$$Cost_p = E_g \times Cost_{ef} \quad (10)$$

where E_g is the electricity consumption (kWh) for the grinding processes, and $Cost_{ef}$ refers to the unit price of electricity (USD/kWh); see Table 2 for details.

The cost of avoiding landfill for steel slag is calculated according to Equation (11):

$$Cost_a = W_s \times D_a \times Cost_{tf} \quad (11)$$

where D_a represents the distance from the steel slag to the landfill (km).

2.5. Sustainability Index

In order to realize the wide application of steel slag partially replacing cement in soft soil stabilization, the sustainability efficiency of SCSs needs to be studied, considering their mechanical properties, carbon emission, and cost. Damineli et al. [38] proposed the carbon emissions required to achieve a strength of 1 MPa as an indicator for material evaluation. Based on this method, the SCS sustainability indices are obtained by Equations (12) and (13). The unconfined compressive strength (UCS) of SCSs and the CO_2

and cost calculated from Equations (1) and (7) are normalized using S-C as the basis, as shown in Equations (14)–(16). Obviously, a lower index indicates better sustainability of SCSs. Taking S-C with a sustainability index of 1 as the benchmark, if both sustainability indices of an SCS scheme are less than 1, it indicates that the scheme has better sustainability than S-C and can be used as a preliminary screening design scheme to provide a decision reference for designers.

$$SUI_{environment} = \frac{N_{CO_2}}{N_{UCS}} \quad (12)$$

$$SUI_{economic} = \frac{N_{Cost}}{N_{UCS}} \quad (13)$$

$$N_{CO_2} = \frac{CO_2}{R_{CO_2}} \quad (14)$$

$$N_{Cost} = \frac{Cost}{R_{Cost}} \quad (15)$$

$$N_{UCS} = \frac{UCS}{R_{UCS}} \quad (16)$$

where $SUI_{environment}$ is the sustainability environment index of SCSs, and $SUI_{economic}$ is the sustainability economic index of SCSs. N_{CO_2}, N_{Cost}, and N_{UCS} are the normalized values of CO_2, cost, and UCS based on S-C. R_{CO_2}, R_{Cost}, and R_{UCS} are the CO_2, cost, and UCS of the reference stabilized soil S-C.

3. Design and Development of Ontology Framework

3.1. System Framework

The open-source software Protégé is used to develop the ontology framework for the evaluation of stabilized soils (OntoESS). The OntoESS framework consists of the database layer, the knowledge base layer, and the user layer, as illustrated in Figure 2. The database layer contains knowledge content such as the stabilizer production process, material properties, energy information, etc., which can be obtained through books and literature, the life cycle inventory (LCI) database, stabilized soil tests, etc. The knowledge base layer is the core of the ontology framework. Domain knowledge is transformed into the ontology model and semantic web rule language (SWRL) through the rule editor, and stored in the knowledge base in the form of the OWL file [39,40]. The predetermined rules can reason new facts through the reasoner. In the user layer, engineers can define semantic query web rule language (SQWRL) query reasoning results based on design requirements to obtain design schemes and optimization directions that meet the requirements [41]. In order to ensure the correctness of the ontology logic construction, knowledge reasoning and consistency checking are realized by the Pellet inference engine.

3.2. The Development of OntoESS

Before the establishment of the ontology model, domain terms need to be collected to form knowledge items, such as involving the steel slag preparation process, including "carbonation, CO_2 captured, etc.". Furthermore, there are complicated semantic relationships among products, activities, and environments in life cycle analysis. To provide an explicit description, life cycle semantics is used in the construction of ontology models, such as the introduction of the terms "process and flow" in ISO 14040. The key concepts and relationships in OntoESS are established using the Unified Modeling Language (UML), as illustrated in Figure 3.

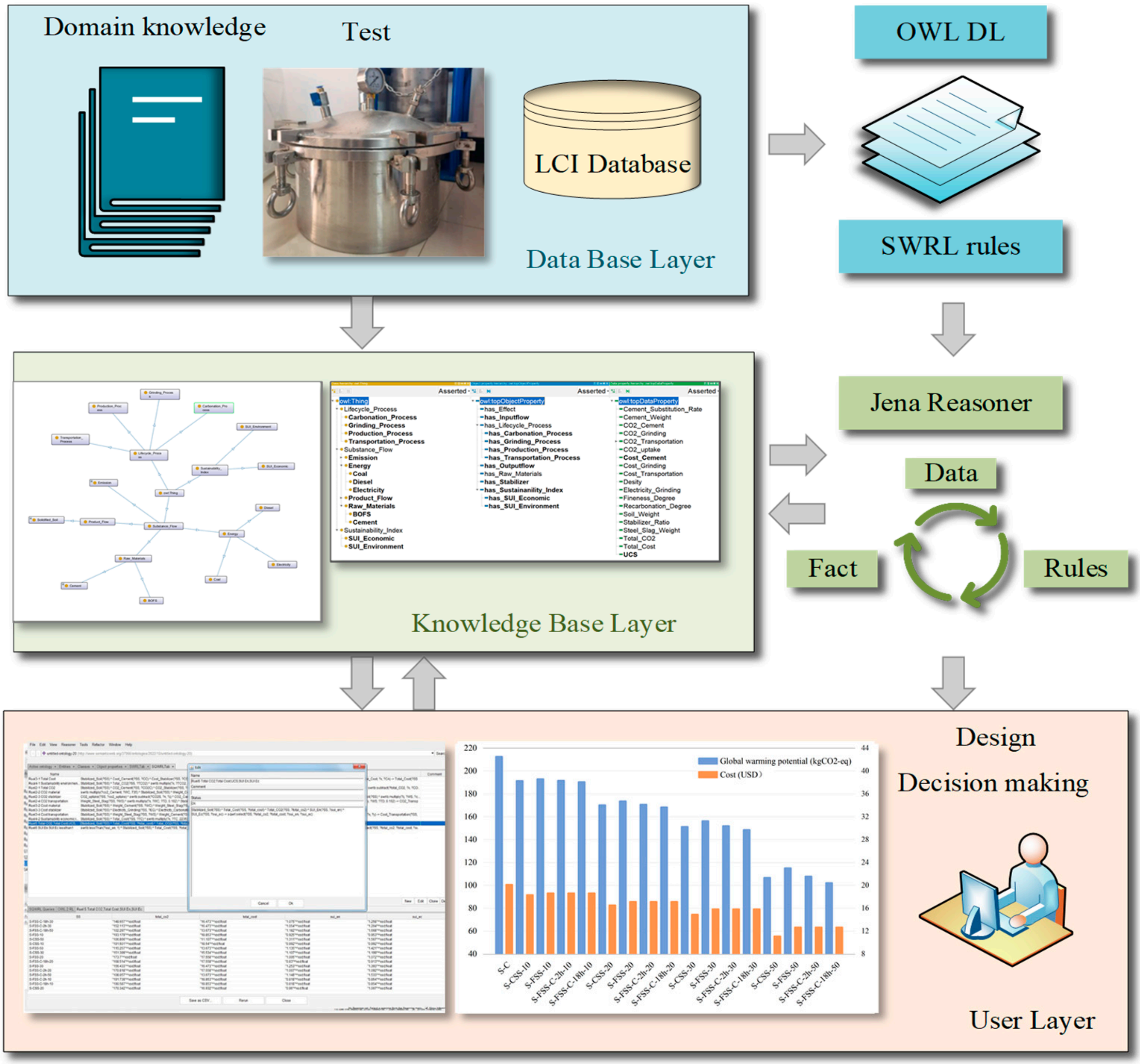


Figure 2. The developed ontology framework.

3.2.1. Define Hierarchy and Classes

The ontology model based on life cycle semantics is shown in Figure 4. The top-level classes involving stabilizer production mainly include the elementary flow, process, and product flow classes. The elementary flow class has two subclasses, the resource and emission classes. Resources are energy (diesel, coal, etc.) and raw materials (cement, steel slag) that enter the production system from the natural environment. Emissions are substances released from the production system to the air, water, or soil, such as CO_2. The process is used to describe various activities in the product life cycle, including the production process, transportation process, etc. The product flow represents the output of a process or production system, e.g., stabilizers.

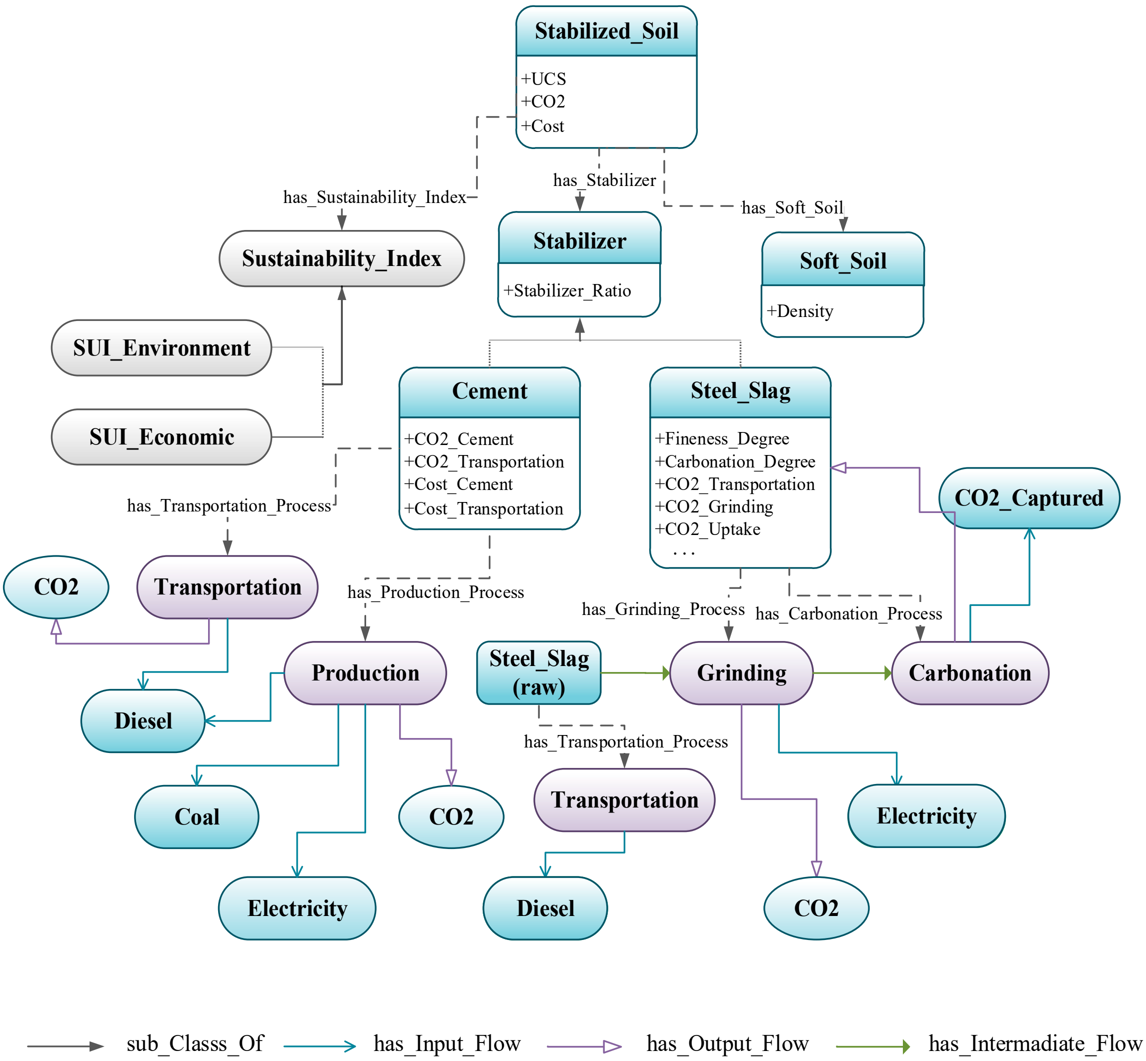
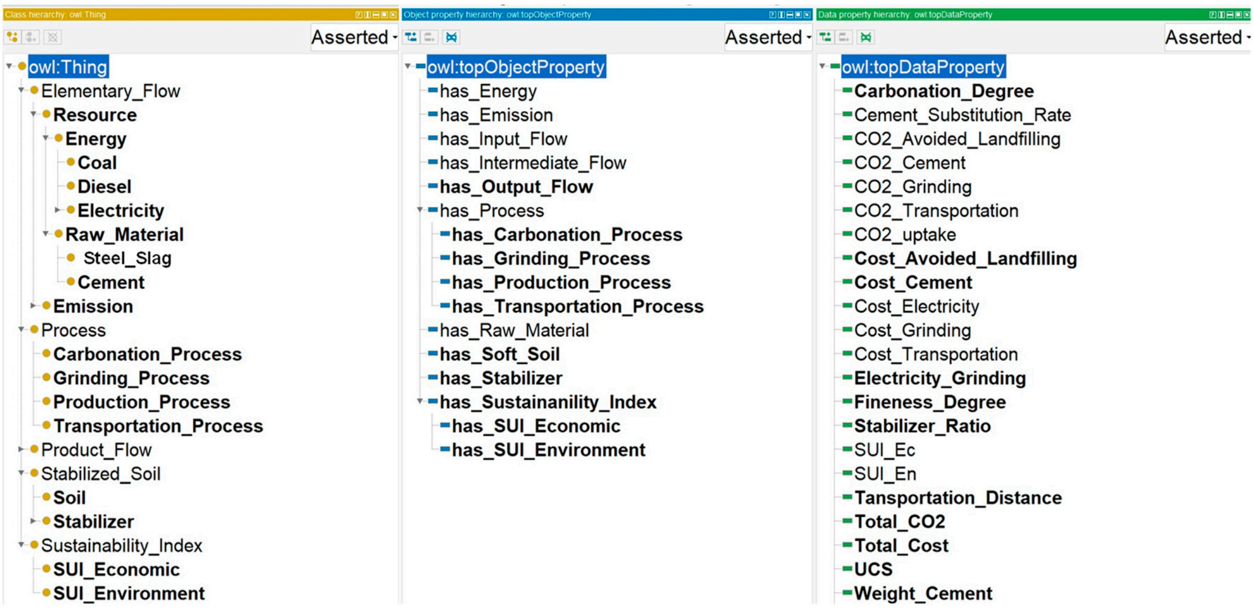


Figure 3. UML class diagram of the key concepts in the ontology.



(**a**) (**b**) (**c**)

Figure 4. Development of ontology in Protégé-OWL 5.2: (**a**) classes, (**b**) object properties, (**c**) data properties.

3.2.2. Define Properties of Classes

Properties of ontology include object properties and data properties. The object properties are used to define the relationships between different classes; for example, the relationship between cement and production is defined as "has _ Production _ Process". The property "has _ Input _ Flow" is set between the process and the material or product entering the process. "has _ Output _ Flow" is placed between the process and the material or product leaving the process. "has _ Intermediate _ Flow" represents the relationship between adjacent processes in the production system. Data properties are used to qualitatively or quantitatively describe the instance properties, such as material weight, strength, carbon emission, etc.

3.2.3. Define SWRL Rules

To enable a comprehensive decision analysis of SCSs, the ontology framework needs to have strong reasoning and computational capabilities. Therefore, SWRL rules are used for function strengthening to calculate carbon emissions, production costs, and sustainability indicators for SCSs. SWRL rules can be combined with the elements defined in the ontology. Generally, SWRL rules consist of class atoms, individual property atoms, data-valued property atoms, and built-in atoms. The atoms are connected by '^', the reasoning and the result are connected by '->', and '?' is used to represent variables. For example, the SWRL rules for calculating the total carbon emissions of SCSs are shown in Table 3, and the SWRL rules for Equations (1)–(16) are shown in Tables S1–S3.

Table 3. The SWRL rules of calculating the total CO_2 emission.

Rule 1	Calculating total carbon emission of SCSs: $CO_2 = CO_{2-m} + CO_{2-t} + CO_{2-p} - CO_{2-a}$ Stabilized_Soil(?SS)^CO2_Cement(?SS,?CO2C)^CO2_Stabilizer(?SS, ?CO2S)^CO2_Transportation(?SS,?CO2T)^ CO2_Avoided_Landfilling(?SS,?CO2a)^swrlb:add(?x, ?CO2C, ?CO2S, ?CO2T)^swrlb:subtract(?total_CO2, ?x, ?CO2a) -> Total_CO2 (?SS, ?total_CO2)

3.2.4. Define SQWRL Rules

SQWRL is an ontology rule query language based on the SWRL extension. After SWRL rule reasoning, engineers can query the relevant information of SCSs according to the design requirements, such as the cost and sustainability indices of each scheme. See Tables S1–S3 for details of the SQWRL rules.

4. Case Study

4.1. Case Study Description

A case study was conducted to demonstrate the practicality of OntoESS in the sustainable evaluation of stabilized soils. The soft soils in this case were sampled from a marine soft soil foundation in Dalian, Liaoning Province, China. The raw materials of the stabilizer were 42.5R Portland cement and steel slag (type for basic oxygen furnace slag). The physical properties of soft soils are shown in Table 4 [18]. According to the unified soil classification system ASTM-2487, the soil was classified as low plasticity clay (CL). Table 5 shows the chemical composition of soft soil, cement, and steel slag [18]. The transportation distances of the raw materials are listed in Table 6.

Table 4. Basic physical properties of soft soil.

Parameter		Value
Initial water content (%)		61.12
Liquid limit (%)		38.2
Plastic limit (%)		19.2
Plasticity index		18.7
Clay fraction (%)	<0.002 mm	5.1
Silt fraction (%)	0.002–0.075 mm	55.2
Sand fraction (%)	0.075–2 mm	39.7
Optimum water content (%)		11.7
Maximum dry density (g/cm^3)		1.92

Table 5. Chemical compositions of soft soil, cement, and steel slag (w/w%).

Sample	CaO	SiO_2	Fe_2O_3	Al_2O_3	MgO	MnO	TiO_2	Others
Soft soil	5.6	43.8	8.65	22.50	6.41	-	-	10
Cement	61.12	21.46	2.88	5.25	2.08	-	-	2.5
Steel slag	39.02	14.45	23.42	3.83	7.27	7.31	1.35	1.1

Table 6. Material transportation information.

Material	Transport Distance (km)	
	Plant	Landfill
Cement	21	-
Steel slag	58	35

To investigate the influence of the steel slag fineness, carbonation degree, and substitution rate on the sustainability of SCSs, four kinds of steel slag were prepared, as shown in Figure 5. A ball mill with a capacity of 20−25 t/h and a power of 1500 kW was used for steel slag grinding. The specific surface area of coarse steel slag (CSS) increased from 117.3 m^2/kg to 747.2 m^2/kg after grinding with a ball mill for 1 h, consuming about 75 kwh/t of electrical energy. Only fine steel slag (FSS) was used for carbonation as the finer particle size was found to be more conducive to the carbonation reaction [42]. The FSS mixed with a certain amount of water was uniformly placed in the carbonation chamber and carbonated by a concentration of 99.9% CO_2 under a room temperature and pressure environment (temperature 25 °C, pressure 0.2 MPa). According to the measured weight gain rate of the steel slag after carbonation, the CO_2 *uptake* for fine steel slag carbonated for 2 h (FSS-C-2h) and 18 h (FSS-C-18h) was 5% and 9%, respectively.

Four types of steel slag were mixed with cement at different substitution ratios to form the composite stabilized material, with S-C as the control group, to investigate the effect of steel slag on the strength of the stabilized soil. The total amount of stabilizer ($m_{cement+steel\ slag}/m_{dry\ soil}$) was controlled to be 15%, and the proportion of steel slag replacing cement was 10%, 20%, 30%, and 50%, respectively. Based on the deep mixing method widely used for foundation treatment [43,44], the water content of the specimen preparation was set at 1.5 times the liquid limit, i.e., 57.2%, to ensure the fluidity of the stabilized soil. The specimens were maintained at room temperature for 60 days after demoulding. Design parameters and UCS_{60d} of SCSs and S-C are given in Table 7.

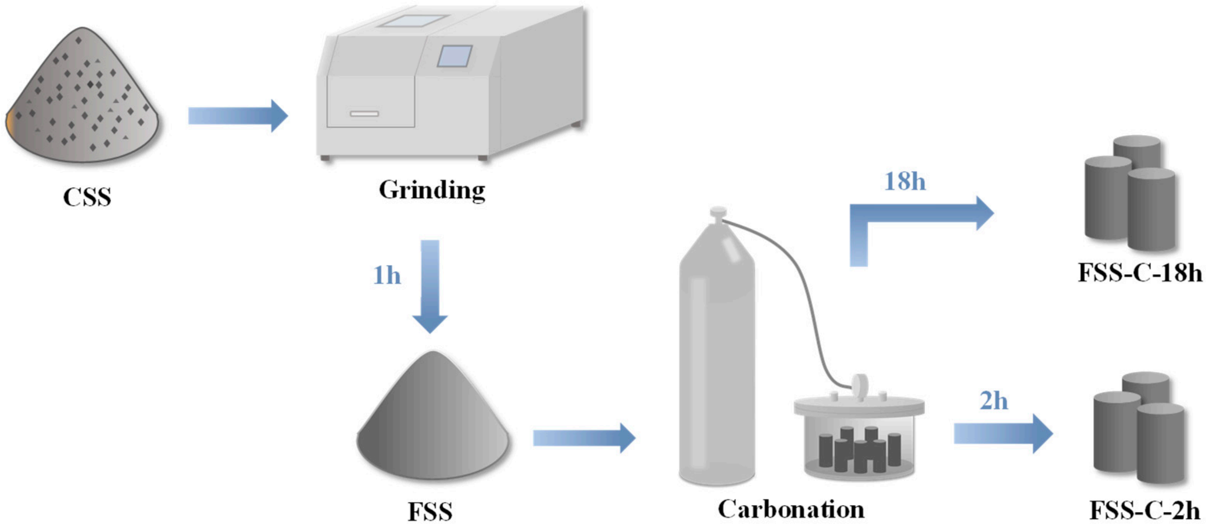


Figure 5. The preparation of the four types of steel slag.

Table 7. Design parameters and UCS_{60d} of SCSs and S-C.

Designated Name	Steel Slag Substitution Ratio (%)	Binder Mixtures (kg)		UCS_{60d} (kPa)
		Cement	Steel Slag	
S-C	0	288	0	2070.2
S-CSS	10	259.2	28.8	1919.92
	20	230.4	57.6	1727.86
	30	204.6	86.4	1331.41
	50	144	144	793.66
S-FSS	10	259.2	28.8	2032.2
	20	230.4	57.6	1681.93
	30	204.6	86.4	1214.95
	50	144	144	988.44
S-FSS-C-2h	10	259.2	28.8	1949.23
	20	230.4	57.6	1651.62
	30	204.6	86.4	1404.69
	50	144	144	916.29
S-FSS-C-18h	10	259.2	28.8	2267.32
	20	230.4	57.6	1975.27
	30	204.6	86.4	1345.3
	50	144	144	842.16

From the strength results in Table 7, with the increase in substitution ratio, the strength generally shows a downward trend. The strength of S-FSS-C-18h with 50% steel slag substitution (S-FSS-C-18h-50) is only 40.7% of that of S-C. Previous studies have found that there is an interaction between steel slag and cement, which can stimulate each other's activity under a certain ratio; however, excess steel slag can hinder the hydration of the cement [45,46]. It is noteworthy that low-content carbonated steel slag can significantly improve the strength of stabilized soil; the strength of S-FSS-C-18h-10 reaches 110% of S-C. This is probably due to the formation of $CaCO_3$ dispersed in the cement paste after carbonation of the steel slag to form additional nucleation sites, which promote the hydration of the cement [47].

4.2. The Application of OntoESS

4.2.1. Impact Analysis of Steel Slag Preparation

According to the specimen design in Table 7, individuals of stabilized soil are created in the ontology model. Information such as material amounts, transport distance, and power consumption are input into each individual as data attributes. The calculation rules of Equations (1)–(16) were invoked via the SWRL Tab plug-in and the reasoner is run to perform the rule inference. After the system runs, the individual's carbon emissions and cost results at each stage are automatically generated, as shown in Figure 6.

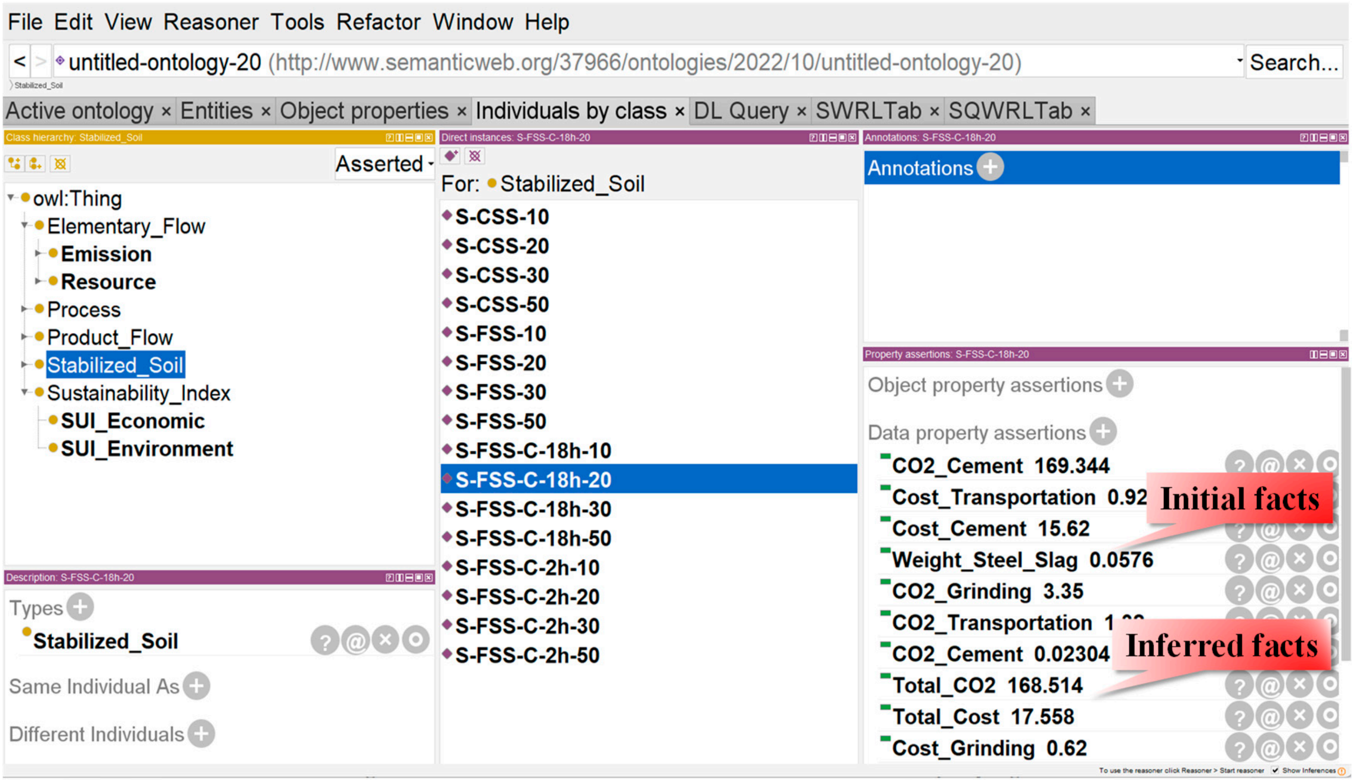


Figure 6. The interface of new fact.

To compare the environmental impacts of the four steel slag preparation processes, S-CSS-20, S-FSS-20, S-FSS-C-2h-20, and S-FSS-C-18h-20 were used as examples; according to the above method, the carbon emissions of the four equivalent steel slags during transport, grinding, carbonation, and avoided landfilling were queried, and the results are shown in Table 8. Electricity consumption during the grinding process is the main contributor to the GWP of steel slag; FSS has the highest GWP of the four kinds of steel slag, reaching 3.56 kgCO_2-eq. Carbonated fine steel slag (FSS-C-2h, FSS-C-18h) can reduce GWP due to the absorption of a certain amount of CO_2, of which FSS-C-18h achieved a negative GWP −1.62 kgCO_2-eq due to the longer carbonation time. Fuel consumption from the transportation process and avoided landfilling has little contribution to GWP, which is mainly related to transport distance. From the environmental impact perspective, the adverse effects of the steel slag transportation and preparation process can be almost offset by the *CO_2 uptake* and avoided landfilling.

Table 8. GWP of the four types of steel slag (kgCO_2-eq).

Types	Transportation	Avoided Landfilling	Grinding	CO_2 Uptake	Total
CSS	0.54	−0.3265	-	-	0.2135
FSS	0.54	−0.3265	3.35	-	3.5635
FSS-C-2h	0.54	−0.3265	3.35	−2.88	0.6835
FSS-C-18h	0.54	−0.3265	3.35	−5.814	−1.6205

4.2.2. Impact Analysis of SCSs

Engineers can also use the SQWRL plug-in to query the specified results according to the design requirements. The carbon emissions, costs, and sustainability indices of each scheme are shown in Figures 7–9.

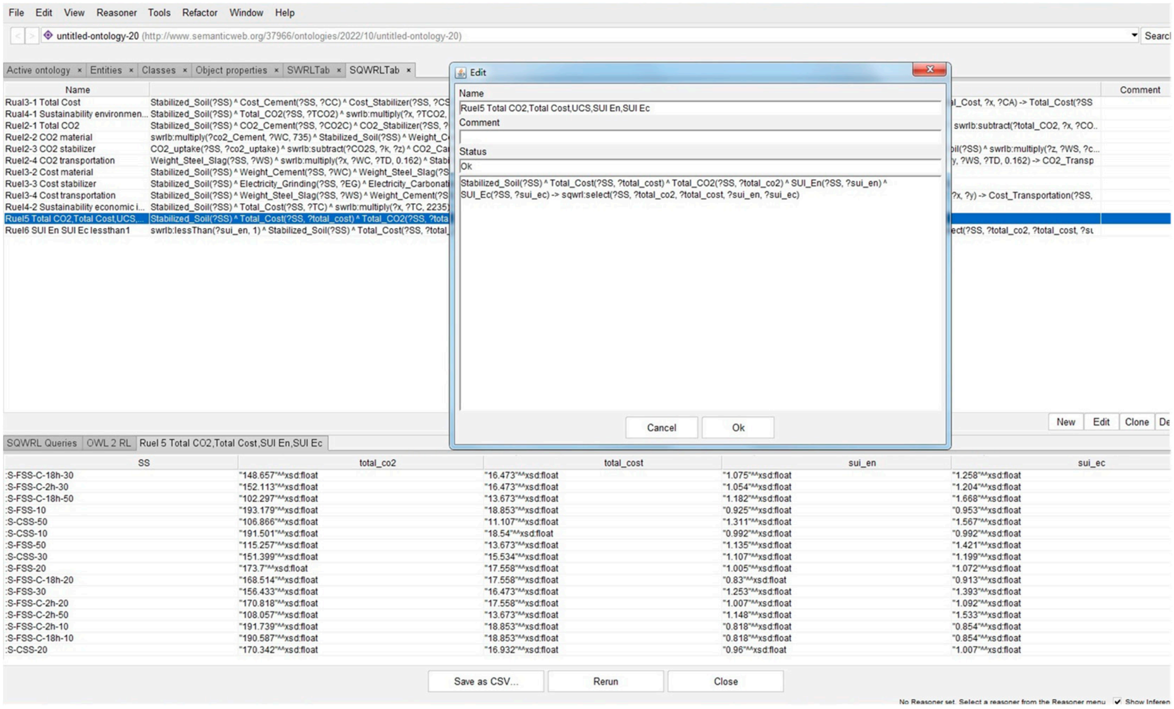


Figure 7. The execution and results after running the SQWRL rules of the query SCS indicators.

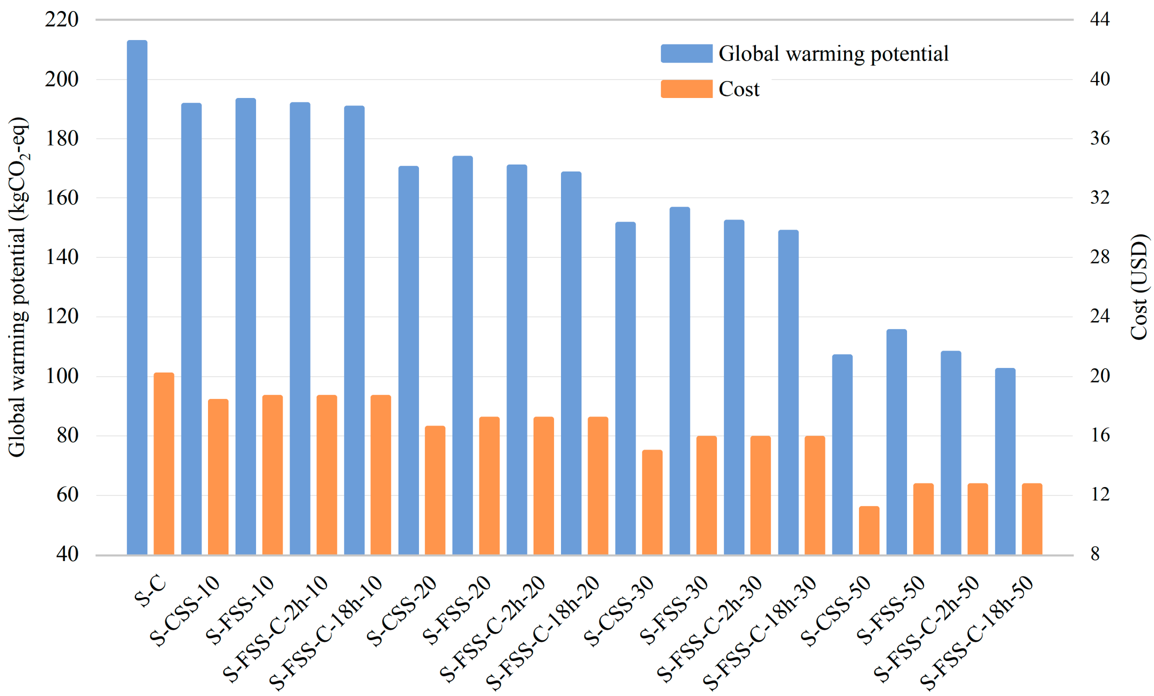


Figure 8. Querying results of GWP, Cost.

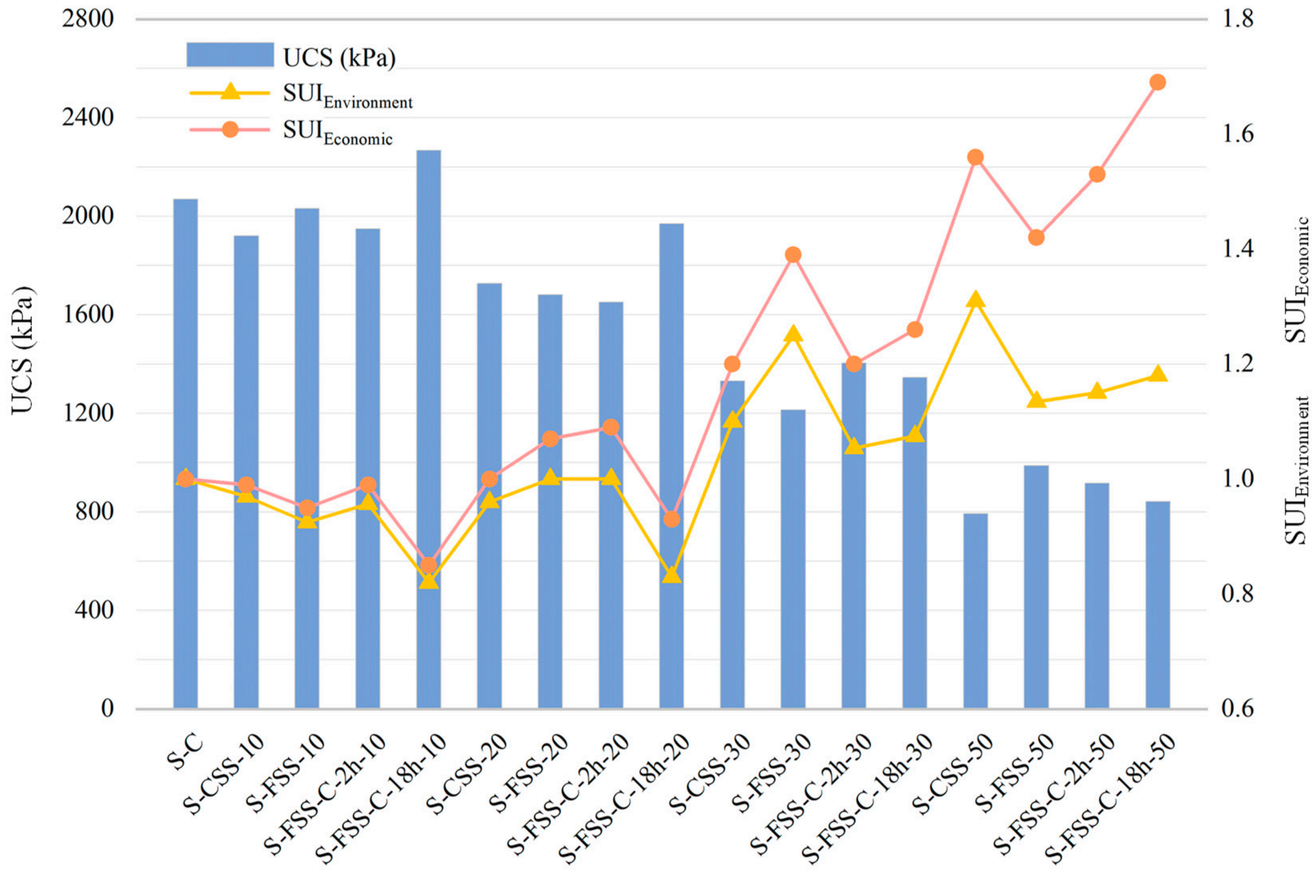
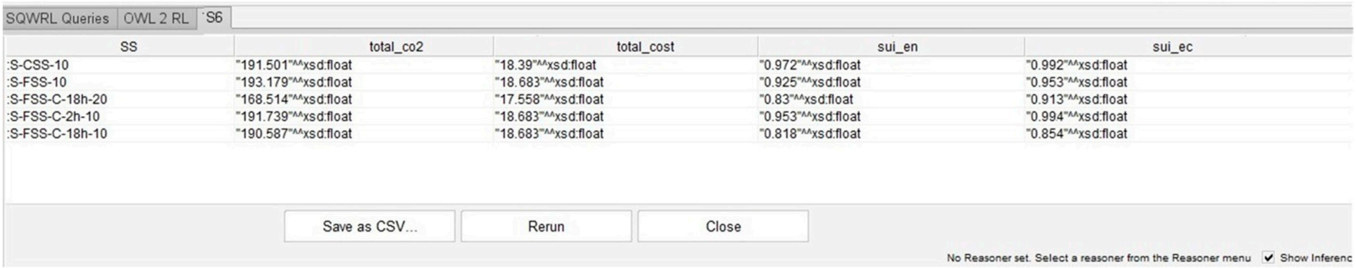


Figure 9. Querying results of $SUI_{Environment}$, $SUI_{Economic}$, and UCS_{60d}.

Figure 8 presents the GWP and cost of the S-C and SCSs. The difference in GWP from the steel slag preparation is not evident in the stabilized soil, because more than 90% of the GWP from stabilized soil is from cement production, which results from the high energy consumption of the cement production processes. Meanwhile, the cement cost reaches more than 70% in each scheme due to the high cement price. With the steel slag substitution ratio increase, the GWP and cost of SCSs decreased significantly. When the substitution ratio is 50%, the GWP and cost of S-FSS-C-18h are 48.1% and 70% of S-C, respectively.

Figure 9 shows the UCS_{60d} and sustainability indices of each scheme. Steel slag as an SCM can effectively reduce the GWP and production cost of the stabilized soil by partially replacing cement. However, cement is the main source of its strength [48], and excess steel slag can cause insufficient strength of the stabilized soil, thus leading to a high sustainability index of the stabilized soil, which is not conducive to engineering applications. We set the strength of the stabilized soil to meet the strength grade 1.0 as required by GJ/T 526-2018 [49], which means that the strength of the specimen should be greater than 1 MPa and, therefore, the steel slag substitution ratio should not exceed 50%. The schemes with both $SUI_{Environment}$ and $SUI_{Economic}$ of less than 1 can be preliminarily selected by running the SQWRL rule. The results are shown in Figure 10. The stabilized soil with low-content steel slag has better sustainability than S-C, and the strength is not less than 90% of S-C. Among them, S-FSS-C-18h-10 and S-FSS-C-18h-20 have the best sustainability with a GWP reduction of 10.4% and 20.4% compared to S-C, respectively.



SS	total_co2	total_cost	sui_en	sui_ec
:S-CSS-10	"191.501"^^xsd:float	"18.39"^^xsd:float	"0.972"^^xsd:float	"0.992"^^xsd:float
:S-FSS-10	"193.179"^^xsd:float	"18.683"^^xsd:float	"0.925"^^xsd:float	"0.953"^^xsd:float
:S-FSS-C-18h-20	"168.514"^^xsd:float	"17.558"^^xsd:float	"0.83"^^xsd:float	"0.913"^^xsd:float
:S-FSS-C-2h-10	"191.739"^^xsd:float	"18.683"^^xsd:float	"0.953"^^xsd:float	"0.994"^^xsd:float
:S-FSS-C-18h-10	"190.587"^^xsd:float	"18.683"^^xsd:float	"0.818"^^xsd:float	"0.854"^^xsd:float

Figure 10. Query results for schemes with $SUI_{Environment}$ and $SUI_{Economic}$ of less than 1.

4.2.3. Sensitivity Analysis

While this case demonstrates the viability of steel slag as a soft soil stabilizer, the fuel consumption for material transportation can also significantly affect the sustainability of the stabilized soil. Improper selection of steel slag suppliers may be contrary to the design intention to reduce the carbon footprint and cost. Therefore, a sensitivity analysis of steel slag transportation for S-FSS-C-18h-10 and S-FSS-C-18h-20 is selected to determine the maximum transport distance that meets sustainable design requirements and inform the designer's selection of suppliers.

The pure cement stabilizer production (21 km transport distance from the cement production site to the stabilizer plant) is taken as the base scenario to assess the environmental and cost impacts of increasing the transport distance from the steel slag production site to the stabilizer plant. The transport distance to achieve the GWP and production cost of a pure cement stabilizer is used as the maximum transport distance for steel slag (D_{smax}), calculated according to Equations (17) and (18). The SWRL calculation rules are shown in Tables S1–S3. The results are shown in Figure 11. Arriving at the same GWP as S-C, the steel slag transport distances ($D_{smax\text{-}GWP}$) for S-FSS-C-18h-10 and S-FSS-C-18h-20 are 4794.55 km and 4791.55 km, respectively, indicating that the effect of steel slag transport on the GWP is not significant and that considerable environmental benefits can be achieved even over long distances. The effect of steel slag transport distance on the cost of stabilizer production cannot be ignored. To achieve lower costs than S-C, it is recommended that the transport distance of steel slag ($D_{smax\text{-}Cost}$) for S-FSS-C-18h-10 and S-FSS-C-18h-20 is controlled to within 379 km.

$$D_{smax-GWP} = \frac{212.66 - (CO_2 - CO_{2-ts})}{W_s \times 0.162} \quad (17)$$

$$D_{smax-Cost} = \frac{18.85 - (Cost - Cost_{ts})}{W_s \times 0.14} \quad (18)$$

where $D_{smax-GWP}$ is the maximum transport distance of steel slag to reach the benchmark scenario GWP, and $D_{smax-Cost}$ is the maximum transport distance of steel slag to reach the benchmark scenario cost. CO_2 and $Cost$ are the carbon emission and cost of SCSs in the initial scenario, respectively. CO_{2-ts} and $Cost_{ts}$ are the carbon emission and cost of steel slag transportation in the initial scenario, respectively.

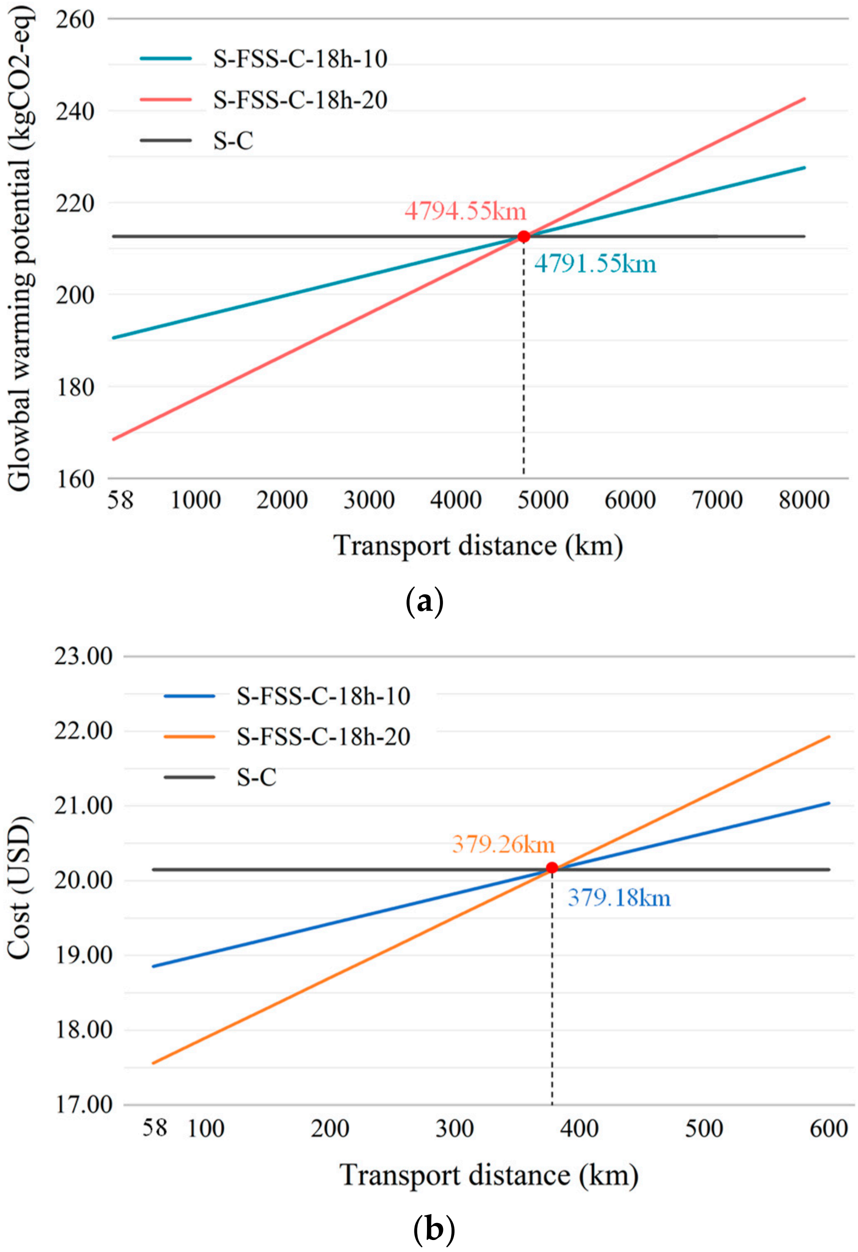


Figure 11. Sensitivity analysis for the steel slag transport distance: (**a**) global warming potential, (**b**) production cost.

5. Discussion

Cement is the most commonly used soft soil stabilization material for foundation treatment in coastal engineering, but the environmental problems caused by the high carbon emission of its production have gradually attracted the attention of all countries. The use of steel slag to partially replace cement to stabilize soft soil has caused widespread concern among researchers. The ontology framework proposed in this study fills the gap in the research on the sustainability evaluation of cement–steel-slag-stabilized soils, because most of the current evaluation studies on stabilized soils only focus on one or two aspects of engineering performance, the environment, and the economy [50,51], failing to integrate the indicators from the perspective of sustainability, and the results of their evaluations are difficult to use for providing references for designers.

From the study results, the steel slag treated by grinding and carbonation can obtain better sustainability than S-C by replacing the cement to stabilize soft soil with a lower content, demonstrating the feasibility of steel slag for soft soil stabilization. However, long transport distances for steel slag should be avoided so that the cost advantages of SCSs are not masked. It should be noted that the preparation of stabilizers in this study was carried out at the laboratory scale. In the future, the influence of the equipment and labor factors required for the mass production and on-site construction of stabilizers should be considered. In addition, durability is also a focus of future research on the sustainability of stabilized soils. Based on the flexibility and reusability of the ontology framework, it can be improved and extended according to new materials and processes, and tools with unified interfaces can be developed for different projects and phases, so as to realize the efficient and collaborative design, operation, and maintenance management of stabilized soils in the whole life cycle.

6. Conclusions

In this study, an ontology framework was developed to evaluate the sustainability of stabilized soil with a cement–steel slag blend (SCSs). Firstly, a quantitative approach for sustainability evaluation indicators of SCSs based on LCA was proposed. Then, an SCS ontology model was developed, and related domain knowledge and basic data are integrated into the knowledge base. According to the semantic web rules, the reasoning and query of evaluation indices were further realized. The ontology framework proposed in this study can clearly describe the logical relationship between production activities and the environment during the life cycle of SCSs, which helps designers to clarify the influence of materials and processes on the sustainability of stabilized soils, and then obtain the optimal design and optimization direction from a macro perspective.

The practicability of the proposed ontology framework was verified by a case of marine soft soil stabilization. The case study found that the four types of steel slag can achieve better sustainability than pure-cement-stabilized soil (S-C) at a lower content. The stabilization of soft soils with FSS-C-18h with 10% and 20% substitution rates represented the best stabilization scheme, achieving similar strengths to S-C while significantly reducing carbon emissions and costs. From the sensitivity analysis of the transport distance of steel slag, even if the transport distance of steel slag is significant, SCSs are still favorable to the environment. However, the transport distance of steel slag greatly affects the cost, which must be considered when selecting suppliers.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/jmse11071418/s1, Table S1: The SWRL rules of calculating CO_2 emission; Table S2: The SWRL rules of calculating cost; Table S3: The SWRL rules of calculating the Sustainability Index; Table S4: The SQWRL rules of selecting all the information; Table S5: The SQWRL rules with Sustainability Index less than 1; Table S6: The SWRL rules of calculating D_{smax}.

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