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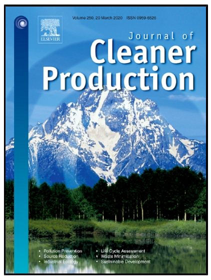

A Sustainability Comparison between Green Concretes and Traditional Concrete Using an Emergy Ternary Diagram

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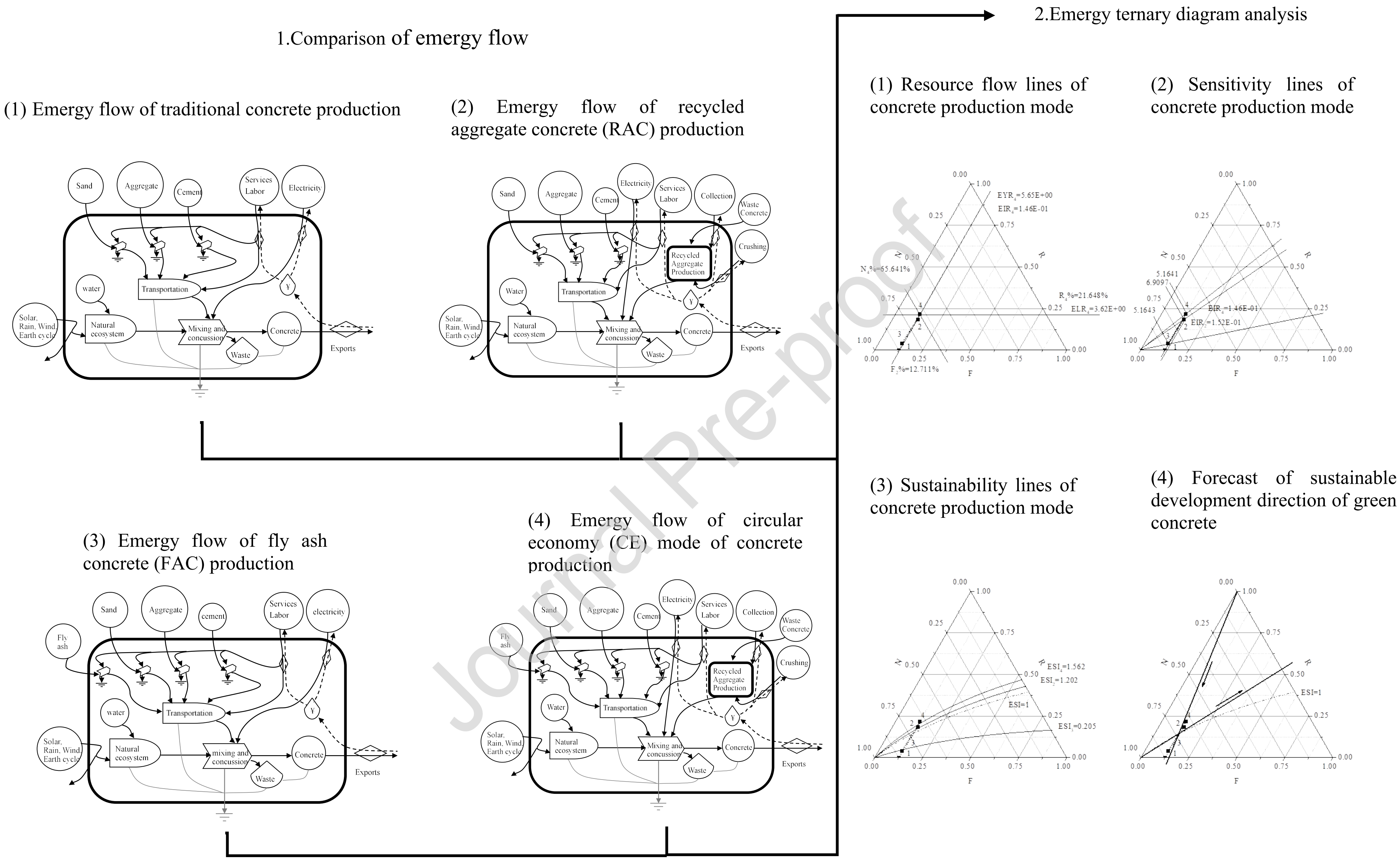
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Mixing and concussion
Concrete
Waste
Exports
Collection
Waste Concrete
Crushing
Recycled Aggregate Production
Fly ash
Y
N
R
F
ESI=1

A Sustainability Comparison between Green Concretes and Traditional Concrete Using an Emergy Ternary Diagram

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ABSTRACT: The sustainable development of green concrete consumes as few natural resources as possible during production and uses and utilizes recyclable waste materials as raw materials. This study summarizes three modes of green concrete production: recycled aggregate concrete production mode, fly ash concrete production mode, and circular economy concrete production mode, as well as the system emergy flow of each mode of production, and presents emergy analysis methods for each mode. With the help of emergy ternary diagram auxiliary lines, the emergy ternary diagram expressions of three green concrete production modes and traditional concrete production modes are analyzed, respectively. The ternary diagram of emergy analysis directly reflects the resource allocation of the system. The relationship between the emergy utilization ratio and the indicators of the system is analyzed, and the sustainability of the existing concrete production system is evaluated comprehensively. The R-resource line corresponds to the environmental load ratio. The closer the R-resource line is to the F-axis, the greater the environmental pressure of the system. The N-resource line corresponds to emergy yield ratio and emergy investment ratio. The closer the N-resource line is to the N-axis, the greater the energy input-output efficiency of the system. The closer the N-resource line is to the "0" point of the R-axis, the higher the

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utilization rate of outsourced resources. In the emergy ternary diagram, it is evident that the circular economy concrete production mode is more sustainable than the other three concrete production modes. Combined with the analysis of the sensitivity line and sustainability line, it is predicted that the concrete production mode along the direction of the R-Sensitivity line is a sustainable development path.

KEYWORDS: Sustainability; Recycled aggregate; Green concretes; Emergy; Evaluation

1. Introduction

China's concrete production ranks first in the world; its annual concrete production is 53% greater than the total of all other countries worldwide. Further, China's cement production is the highest worldwide as well. Its output in 2012 was 2.15 billion metric tons, 8.6 times that of India, the second highest producer, and 29 times that of the United States, the third highest producer (Oh et al. 2014). In China, concrete products and components, concrete mixing stations, and other construction methods are adopted, and about two billion cubic meters of concrete are used in national projects and infrastructure construction annually. According to statistics regarding the production and operation of the national key ready-mixed concrete enterprises (groups), put out by the China Concrete and Cement Products Association, the actual output of ready-mixed concrete enterprises (groups) in China totaled 2.103 billion cubic meters in 2017. Thus, related quality and environmental protection problems about concrete production can not be ignored.

As the most used building material in construction projects, concrete has a great impact on ecological resources (Chen et al. 2019, Taha & Benzaazoua 2019, Timu et al. 2019).

In the initial stage of construction, traditional concrete production enterprises invest heavily in economy and technology; however, following a large-scale production, there are no necessary environmental protection measures for dust, sewage discharge, or noise isolation in the concrete production process. It is necessary to reduce energy consumption in the production and use of concrete (Ngo et al. 2017, Song et al. 2018). This is important for concrete greening and should promote the development of concrete in an environmentally friendly and biocompatible direction (Marinković et al. 2017). With the development of the construction industry, green concrete production has been adopted to replace the traditional mixing of concrete construction sites, which has produced great social and economic benefits in terms of productivity, quality, resources, and environmental protection (Suhendro 2014).

Green concrete has higher strength and durability than traditional concrete. It can meet the requirements of structural mechanics, function, and service life. It functions well and can be used to build a gentle, comfortable, and convenient living space for humans (Turk et al. 2018).Green concrete is an environmentally friendly concrete material that does not only reduce the ecological load on the natural environment during the production process, but also coordinates with the ecosystem on which human beings depend for survival, and be used for building activities (Liew et al. 2017). The application of green concrete follows the “3R” technology of reduction, reuse, and recycling to reduce greenhouse gas emissions; reduce the utilization of natural resources such as limestone, shale, clay, and natural water; and promote the use of waste materials in concrete production. The characteristics of green concrete production include harmony with the natural environment, reducing the load on Earth's environment, realizing the recyclable use of non-renewable resources, saving energy. During the production of green concrete, the amount of cement used is greatly reduced, so as to reduce the waste “by-products” and reduce the “greenhouse effect” and the formation of acid rain in some areas caused by the large amount of CO_2 and SO_2 emissions (Fan et al. 2018, Zhang et al. 2018). Resource-based garbage building materials (also known as green building materials, ecological building materials, environmental protection building materials, and health building materials) have become an important research topic (Jami et al. 2015, Lu et al. 2019). The use of industrial waste (e.g., fly ash and coal gangue), tailings slag, and construction waste (e.g., abandoned concrete, waste brick, and waste mortar) should be minimized to reduce pollution of the natural environment (Wei et al. 2016, Chen et al. 2016, Marinković et al. 2017).

The end goal is that reused resources can be recycled, the load on the Earth and ecosystem can be reduced, and non-renewable resources can be recycled. Therefore, using waste concrete as a recycled aggregate to produce recycled concrete has very important significance for environmental protection and natural resource protection, and it should be considered a new type of green building material (Ghorbani et al. 2019). With population growth and lifestyle improvement, it is expected that buildings and other infrastructure will increase in the coming years, and the demand for concrete production is expected to increase in the future (Ghorbani et al., 2018). Green building materials are the development direction of civil engineering construction materials. With the development of the construction industry, several studies have considered the production of construction and demolition waste (CDW) as an important renewable resource (Behera et al., 2014). The aggregate formed by cleaning, crushing, screening, and mixing in a certain proportion with a gradation of waste concrete is called recycled aggregate. The concrete made from recycled aggregate partially replacing natural aggregate such as sand and stone is called recycled aggregate concrete. Ahmed (2012) analyzed the performance of recycled coarse aggregate concrete with waste and fly ash from building demolition. It was concluded that concrete containing 25% construction and demolition wastes might exhibit better compressive strength and tensile strength than the control mixture.

At present, there are three green concrete production methods are widely used in engineering practice, including: recycled aggregate concrete (RAC) production, fly ash concrete (FAC) production, circular economy (CE) mode of concrete production. In this paper, by analyzing the emergy flow of each production mode, the emergy analysis method for each mode is proposed. The emergy ternary diagrams of three kinds of green concrete production modes and traditional concrete production mode are analyzed respectively, which shows that CE mode of concrete production is more sustainable, and provides reference for the development direction of green concrete.

2. Literature Review

2.1 Comparison of green concrete production

Green concrete uses at least one type of waste as its concrete component and does not cause environmental damage during the production process. According to the current construction technology for green concrete, fly ash and RAC are the main recycled materials added during green concrete production. The common green concrete production methods are: RAC production mode, FAC production mode, fly ash and recycled aggregate mixing concrete production mode, or CE mode.

To date, many researchers have focused on making better use of industrial wastes and obtaining the formula of FAC that meets the performance indicators. The effect of using different proportions of fly ash to replace cement on the compressive strength and fracture toughness of Portland concrete has been studied. The results show that green concrete with fly ash has high compressive strength and fracture toughness, and 20% fly ash replacement ensures high strength and mature concrete (Golewski 2018). In order to maximize the use of foundry waste sand (WFS) and fly ash as part of the replacement of fine aggregate to synthesize polymer concrete, the latest formulation of fine aggregate + WFS + fly ash mixture accounted for 32% (Venkatesan 2019). In this study, fly ash accounts for 30% of the total replacement cement. Studies have also shown that agricultural natural waste can be used as a partial substitute for aggregates or adhesives in green concrete (Belhadj et al. 2014, Luhar et al. 2019). In the green concrete production process, however, more studies attach great importance to resource utilization of industrial waste and municipal solid waste (Siddique 2010, Tang & Brouwers 2018, Li et al. 2018, El-Didamony et al. 2019). Waste-friendly green concrete mixes a lot of solid waste and additives with industrial waste as raw materials, fully digests industrial waste, disposes of municipal solid waste, and uses a recycled aggregate to realize the recycling of all kinds of waste. Fly ash is a type of high-quality cementitious material, which can be directly added into concrete to replace a certain amount of cement or fine aggregate to make fly ash concrete (FAC). Fly ash has a low hydration heat, a variety of sources, and a low price; therefore, the comprehensive performance of FAC is superior to that of ordinary concrete (Nie et al. 2015). In theory, fly ash could completely replace cement. In fact, if the replacement rate of fly ash for cement exceeds 80%, some chemical activators are needed to activate the activity of fly ash. Generally, the optimal replacement rate is app 30% (Golewski 2018).

The production process of RAC involves the collection, recycling, transportation of waste concrete; the processing of recycled aggregate; and the recovery, processing, addition, and transportation of industrial waste from other enterprises (Dash et al. 2016). During the rapid development of modernization and industrialization, many CDWs have been generated. But the consumption of high-quality aggregate and the increase of aggregate demand make the supply of raw materials scarcer. Moreover, with the increase of transportation costs and transportation volume in some areas, recycled materials tend to become more expensive. Recycling technology of recycled aggregate includes removal of pollutants (e.g., steel, wood, and plastics), screening and classification at different stages, and breaking down the demolished concrete to produce smaller fragments. Higher quality aggregates can also be processed, and efforts are made to stack, crush, pre-classify, classify (pre-crush and post-crush), screen, and remove pollutants according to the degree of pollution and the use of recycled materials (Akbarnezhad et al. 2013).

Recycled concrete waste is undoubtedly a primary focus of researchers in the field of sustainable development. Ghorbani et al. (2019) discusses the influence of recycled concrete mix ratios with different maximum particle sizes on mix mechanics and durability of concrete. The results show that the mechanical and durability properties of concrete are slightly improved by reducing the maximum particle size of recycled aggregate at a given mixing ratio. After blending 25% of recycled aggregate, the mechanical properties of RAC is optimal. Life cycle assessment of RAC shows that the mixture of 50% natural aggregate, 50% recycled aggregate, and 10-40% by-product as cementitious material yields a high compressive strength (Ahmed et al. 2019). Wijayasundara et al. (2018) quantified the indirect environmental impact of the application of RAC in structural concrete and used economic evaluation methods to assess the related external costs and benefits. The results show that the production of RAC has a significant net benefit on the price of natural aggregate concrete, ranging from 9 to 28%, and the replacement rate of RAC is between 30 and 100%. In this study, RAC ratios up to 40% of the total concrete output is calculated.

Measures used to determine whether concrete is green include the following: the number of Portland cement substitutes, manufacturing processes and methods, performance, and impact of life cycle sustainability. Some studies have compared the production of green concrete with that of traditional concrete. Marinković et al. (2017) compared several green concrete mixtures for structures based on scenarios (including construction practices, transportation distances and available materials in Serbia). The index is standardized and summarized, and the impact of each concrete mix ratio is expressed with respect to the global sustainability index. The conclusion shows that the mixture of alkali activated fly ash concrete and natural aggregate and the mixture of RAC with a large amount of fly ash exhibit the best environmental performance. The mixture of RAC and cement binder exhibits the worst performance. Turk et al. (2015) evaluated the mix ratio of green concrete prepared by three different types of industrial by-products (foundry sand, steel slag, and fly ash) from an environmental point of view, by means of life-cycle assessment (LCA), and compared these with the corresponding conventional concrete production. The results showed that the use of substitutes and recycled materials is beneficial to the concrete production industry. Green concrete production should give priority to the scheme based on the combination of recycled aggregate, fly ash, and foundry sand. The study also showed that variable delivery distances of products may have a greater impact than alternative material delivery distances. Chen et al (2019) quantitatively analyzed the engineering properties, costs, energy, and environmental impacts of three kinds of pervious concrete mixtures: ordinary Portland cement pervious concrete (PC-Regular), fly ash pervious concrete (PC-FA), and blast furnace slag pervious concrete (PC-BFS) using LCA. The experimental results showed that the comprehensive performance of PC-FA was the highest, based on engineering performance, cost saving, energy saving, and emission reduction.

2.2 Application of emergy accounting

As a complex industrial ecosystem, green concrete production has many units of input and output, including material flow, energy flow, information flow, and labor flow. When conducting benefit analysis, the system must be treated in a unified dimension. The traditional method of benefit analysis is used to convert inputs and outputs into currency for comparative analysis; in its application, the accuracy and applicability of this method have certain limitations (Hossaini and Hewage 2013). The emergy analysis method is adopted in this study. It is generally believed that the self-organization, transformation, and information paper published by American ecologist H.T. Odum in 1983 in the Journal Science marks the establishment of emergy theory (Brown and Ulgiati 2004). Emergy is the total energy required to make a service or product expressed in energy of one form (Odum HT 1996). The energy of all kinds of resources, products, or services within the human survival system originates directly or indirectly from solar energy. Solar energy is often used to measure the energy value of a certain energy, and its unit is Solar emjoules (Sej) (Jorgensen et al. 2004). The emergy of a resource, product, or service is the total quantity of solar Joules used directly or indirectly in its formation process. The emergy theory and analysis method make it possible to compare and analyze the energy flow, logistics, and other ecological flows of various ecosystems or eco-economic systems that are difficult to measure in a unified way. Emergy is not equal to actual energy, but it is a collection of certain kinds and quantities of energy in a certain time and space (Amaral et al. 2016). Whether renewable resources, non-renewable resources, commodities, services, even information, and education, emergy analysis can be used to evaluate their value (Liu et al., 2015).

Emergy accounting is widely used in green building and green concrete evaluation; Brown and Buranakarn (2003) evaluated municipal solid waste treatment systems and building and demolition wastes based on an emergy life cycle assessment. They found that the emergy per unit mass was suitable for evaluating the recycling capacity of building materials. Chen et al. (2018) evaluated the sustainability of cement production based on the emergy analysis method of life cycle inventory. The results show that the consumption of limestone, coal, and electricity are the main contributing factors to the total energy required for cement production. In such a situation, the cement production in China has brought about a high environmental burden, and it is unsustainable. Pulselli et al. (2008) evaluated the main steps of the concrete production process through emergy analysis: (1) cement production, (2) material transportation, and (3) concrete mixing. The per-unit emergy of cement and concrete was compared with the previous emergy evaluation, and the emergy investment ratio (EIR) is proposed as a comprehensive indicator of sustainability to highlight the sensitivity of emergy analysis to the boundaries of local environments and production systems. The results show that cement and concrete production is highly dependent on external resource flows. In addition, because of the high sensitivity to external instabilities, the higher the EIR, the weaker the competitiveness of the production system. Song and Chen (2016) conducted an emergy analysis of resources, products, and services within the cement production process according to the raw material substitution scheme, and they comprehensively evaluated the impact on the environment. It was pointed out that the use of the ternary emergy diagram to optimize the allocation of various ecological factors in cement production process can overcome the difficulties of traditional emergy analyses of the optimization process.

The aforementioned studies compared green concrete with traditional concrete production process, mainly from the standpoints of concrete performance, material ratio, resource utilization, and other aspects. There is no systematic analysis of labor flow, such as the processes of crushing, sorting, collecting, mechanical processing, and transporting of recycled aggregate. The present study summarizes the circular economy (CE) mode of green concrete production. The system emergy flow of each mode of production is analyzed, and the emergy analysis method for each mode is presented. The emergy ternary diagram expressions of three green concrete production modes and traditional concrete production modes are analyzed and compared.

The emergy of different products is evaluated by multiplying the mass (kg) or energy (j) or currency ($) by the unit emergy (transformity or specific emergy or emergy to money ratio). Unit emergy refers to the solar emergy required to directly or indirectly produce 1 J or 1 kg of products or services or $1 (Odum HT 1996). When evaluating a process, the unit emergy (Sej) of a commonly used product or service can be determined using the previously calculated unit emergy. There are several important types of unit emergy value (UEV) including transformity (Sej/j), specific emergy (Sej/g), emergy per unit money (Sej/$), and emergy per unit labor (Sej/year, Sej/h or Sej/$).

Emergy baseline is the emergy of the main driving energy flow of the geobiosphere, which provides a reference point for the emergy evaluation of all other energy flows using Unit Emergy Value (UEV). Odum et al. calculated values of the total emergy of Earth's biosphere are 9.44E+24 Sej/y (1996) and 15.83E+24 Sej/y (2000), thereafter, Brown and Ulgiati calculated emergy baselines of 15.2E+24 Sej/y (2010) and 12.0E+24 Sej/y (2016). This paper assumes an emergy baseline of 15.83E+24 Sej/y.

From the perspective of the eco-economy, the emergy input of the concrete production system is analyzed. The emergy input includes three categories: (1) renewable resources (R) from the global environment, including solar radiation, rain, wind, and earth cycles, and particularly fresh water or grey water; (2) non-renewable resources (N), such as cements, sands, natural aggregates; and (3) social and economic input (F), mainly labor and services. In the green concrete production system, environmental emissions include solid waste, wastewater, and gases, where solid waste is recycled, and water includes fresh water and grey water that are recognized as renewable resources (R). Natural aggregates, limestone and sandstone, are obtained from mined ore and are therefore classified as non-renewable resources (N). Electricity, transportation, and other resources purchased from the outside, machining, and other paid labor belong to social and economic input (F). Giannetti et al. (2006) takes R, N, F as the three coordinates of ternary diagram, and propose a graphical tool of ternary diagram aided emergy analysis. Graphical representation of emergy accounting data can compare ecosystem service processes and systems. Almeida et al. (2007) further exemplified the emergy ternary diagram to help evaluate the system's dependence on renewable and non-renewable inputs, as well as to assess environmental support for reducing process emissions. Emergy ternary diagram can directly reflect the resource allocation of the system, fully evaluate the sustainability, and predict the development direction of the system (Zhao et al. 2019). In this paper, with the aid of the emergy ternary, the traditional concrete production mode and three green concrete production modes are compared and analyzed.

3. Methods

3.1 Emergy index

The meaning and calculation formula of input-output emergy index of green concrete production system are as follows. (Odum HT 1996, Ulgiati and Brown 1998)

R% is the ratio of renewable emergy input to total emergy input, reflecting the dependence on natural resources.

$$R\% = \frac{R}{R+N+F} \quad (1)$$

N% is the ratio of emergy input of non-renewable resources to total emergy input, reflecting the structure and function of the system.

$$N\% = \frac{N}{R+N+F} \quad (2)$$

F% refers to the ratio of economic emergy input to total emergy input, reflecting the system's dependence on external economy.

$$F\% = \frac{F}{R+N+F} \quad (3)$$

Environmental load ratio (ELR) indicates the environmental pressure of the concrete production system on the surrounding environment.

$$ELR = \frac{N+F}{R} \quad (4)$$

Emergy yield ratio (EYR) indicates the efficiency of system purchasing emergy input.

$$EYR = \frac{Y}{F} \quad (5)$$

Emergy investment ratio (EIR) indicates the economic development degree of concrete production system.

$$EIR = \frac{F}{R+N} \quad (6)$$

Emergy sustainability index (ESI), the ratio of EYR to EIR, reflecting the sustainability of concrete production system.

$$ESI = \frac{EYR}{ELR} \quad (7)$$

3.2 Emergy ternary diagram

To visually describe the energy flow of different systems, Giannetti et al. (2006) and Almeida et al. (2007) proposed an emergy ternary diagram to represent the relationship between the emergy input values in the research system. The auxiliary lines such as Resource flow line, sensitivity line and sustainablity line are drawn in emergy ternary diagram, which is convenient for emergy analysis.

In Figure 1(a), the distance from the point to the opposite side of a resource item represents the relative percentage of the resource component. The resource flow line is a line parallel to the bottom edge of the resource item, which is used to compare the resource utilization structure of the production process. Sensitivity line is shown in Figure 1(b), the line between the point and a vertex in the ternary diagram represents the percentage change of the opposite resource type along this line. The input ratio of the other two types of resources at the point on the line remains constant. In figure 1 (c), the sustainability line is the curve moving from the “0” point of the F-axis to the R edge, dividing the ternary diagram into regions with different levels of sustainability. ESI = 1 divides the ternary diagram into two regions. The first half represents sustainable development, and the second half represents unsustainable development (Giannetti et al. 2006).

[Place Figure 1 here]

4. Results and discussion

4.1 Analysis and comparison of emergy of green concrete production

4.1.1 Traditional concrete production

The emergy input and output of traditional concrete production are shown in Table 1, and Figure 2 shows the emergy flow system diagram of the traditional concrete production mode, in which sand, cement, and gravel are non-renewable resources (N); industrial water is a renewable resource (R); mechanical processing, electricity, services and labor, and transportation are social and economic inputs (F). The final emergy of concrete output is the emergy of products (Y).

[Place Table 1 here]

[Place Figure 2 here]

4.1.2 Recycled aggregate concrete (RAC) production

In the green concrete production process of recycled aggregate, the available construction waste includes waste concrete, waste bricks, and waste mortar. In the past, these construction wastes were only used for ordinary backfilling projects, or were used for roadbeds, cushioning of roads, and foundation reinforcement after sorting and crushing (Bassani et al. 2019). Furthermore, with the improvement of construction technology and quality control level of green concrete, RAC is increasingly used in engineering structures. The cost of demolition, transportation, and recycled aggregate processing of waste concrete is calculated into the cost of green concrete production; the cost of green concrete production is sometimes higher than that of traditional concrete production using natural aggregate (Rao et al. 2007). However, if the materials can be obtained locally with respect to the construction site and sorted, broken, decomposed, and graded at the time of demolition, the cost can be greatly reduced. When the cost of concrete, brick, slag, and other construction materials is too high, and the construction material resources are scarce at the project site, the efficiency of green concrete will increase.

In this study, a 40% ratio of recycled aggregate to of RAC production was calculated. The input and output emergy of RAC are shown in the Table 2, and Figure 3 is the emergy flow system diagram of RAC production mode.

[Place Table 2 here]

[Place Figure 3 here]

4.1.3 Production of fly ash concrete (FAC)

Fly ash is one of the industrial wastes with large discharge at present. With the development of the power industry, fly ash emissions from coal-fired power plants are increasing annually. If a large quantity of fly ash is not properly treated, it will generate dust, fog, and haze, causing air pollution. If discharged into the water circulation system, it will cause water pollution and river siltation. Furthermore, fly ash as industrial residue sometimes contains toxic chemicals, which can cause harm to humans and biological health.

The treatment and utilization of fly ash has attracted wide attention. Fly ash has pozzolanic activity and can be used as a granular building material, saving raw material resources, land, energy consumption, and protecting the ecological environment. The main raw materials for FAC production include fine aggregate, fly ash, water, cement, and sand. After calculating the ratio of raw materials, processing and mixing, pouring and molding, curing, and other processes, FAC is made. With the development of technology, the price of deep-processed FAC is very cheap. The application of grinding slag technology can make fly ash not only a substitute for raw materials (or part of the substitute), but also an admixture in ordinary concrete blocks and lightweight aggregate concrete blocks (Zawawi et al. 2019). When fly ash partially replaces cement mixing concrete, the amount of cement added is greater than that of original cement. In this study, 30% of cement was replaced by fly ash at a ratio of 1.4:1.

Table 3 is the emergy calculation of input and output of concrete production mode mixed with fly ash. Among them, Figure 4 is the emergy flow system diagram of concrete production mode mixed with fly ash.

[Place Table 3 here]

[Place Figure 4 here]

4.1.4 Circular economy (CE) mode concrete production

The CE production mode attaches great importance to the generation and discharge of waste. The CE production mode is the production mode of qualified concrete based on the comprehensive treatment of construction waste. The recycling economy mode of concrete production can utilize construction waste including waste concrete, fly ash, coal gangue, waste cement and mortar, recycled glass, and light ceramics. At present, the most widely used green concrete production technology is mainly to mix fly ash in the production process of recycled concrete, which can reduce the disposal of waste concrete and industrial waste residue, two common pollution sources, at the same time. In this study, the production of recycled concrete mixed with fly ash is taken as the research object, and an emergy analysis of the CE concrete production mode is carried out. The calculation results are shown in Table 4. The emergy flow system diagram of CE concrete production mode is shown in Figure 5.

[Place Table 4 here]

[Place Figure 5 here]

4.2 Calculation of Emergy Index of Green Concrete Production

Formulas (1)-(7) are used to calculate the evaluation indicators of green concrete production mode; Table 5 compares the emergy analysis indicators of traditional concrete (1), RAC (2), FAC (3), and CE concrete (4) production modes.

[Place Table 5 here]

4.3 Emergy ternary diagram analysis

4.3.1 Resource flow line analysis

Figure 6 is the emergy ternary diagram of green concrete production. Four points in the diagram represent “traditional concrete production mode,” “FAC production mode,” “RAC production mode,” and “CE concrete production mode” from point1 to point4. The point in the ternary diagram is determined by the proportion of three different types of resources. The R-resource flow line corresponds to the emergy index ELR; as the R-resource flow line approaches the F-axis, the higher the ELR and ecological environment pressure of the concrete production system. The order of ELR values is CE concrete (4) < RAC (2) < FAC (3) < traditional concrete (1). Therefore, the green concrete production modes of mixing in recycled aggregate and fly ash have the best environmental compatibility. Further, the ELR of the RAC production mode is 4.42 E+00, which is 81.7% lower than that of FAC, indicating that the system environmental pressure of RAC production mode is lower than that of FAC production mode. Compared with the traditional concrete production mode, the ELR of the three green concrete production modes is greatly reduced, and the ELR of the CE concrete production mode (3.62E+00) is the lowest. This demonstrates that the CE concrete production mode can treat waste concrete and industrial waste residue as raw materials comprehensively, so that the whole concrete production system can be optimized in both economic and environmental aspects.

The resource flow line F corresponds to the emergy indicators EYR and EIR; as the F-resource flow line approaches the N-axis, the higher the EYR and the higher the input-output rate. As the line approaches the "0" point of the R-axis, the EIR increases, indicating a higher productivity of the system. Figure 6 shows the similarities between the CE and RAC production modes. Comparing their emergy indicators (EYR and EIR), the CE concrete production mode has the highest EYR of 5.65E + 00, and the RAC production mode EIR (1.52E-01) is slightly higher than that of the CE concrete production mode. It shows that CE concrete production mode has the highest emergy output benefit. As a result of improvements to production technology and large amounts of capital input, the use efficiency of social purchased emergy of the RAC production mode is not as efficient as that of CE concrete production mode.

[Place Figure 6 here]

4.3.2 Sensitivity line analysis

The R% of the traditional concrete (1) production mode is approximately equal to 0, which tends to approach the F-axis along the sensitivity line R of the N/F ratio. The other three lines starting from the "0" point of N-axis represent the lines of the FAC (3), RAC (2), and CE concrete (4) production modes. The emergy input of non-renewable resources (N) and social service emergy (F) is stable according to the N/F ratio; the value of N/F at all points on the R-sensitivity line remains unchanged. As the points approach the vertex of the R-axis, the EIR decreases, and the utilization efficiency of purchased energy in the system increases. The R-sensitivity line of the traditional concrete production mode can be approximately regarded as the F-axis, the emergy of renewable resources that invested in the traditional concrete production process is too small, and the dependence on non-renewable resources is the greatest.

The input of non-raw material resources is negatively correlated with the input of recycled aggregate and fly ash. The N/F ratio of the CE concrete production mode is 6.91, which is greater than that of the FAC and RAC production modes. This shows that the CE concrete production mode has less input of non-raw materials resources than the other two concrete production modes, but it has a higher efficiency of renewable resource utilization.

[Place Figure 7 here]

4.3.3 Sustainability line analysis

In Figure 8, the sustainability lines of the RAC and CE concrete production modes are located in the sustainability region. The emergy sustainable index ESI of the RAC production mode is 1.20. Although it is much greater than those of the traditional concrete and FAC production modes, it smaller than that of the CE concrete production mode ESI (1.56). This demonstrates that the sustainability of RAC and FAC is inferior to that of the CE concrete production mode. In Table 5, the ESI of the CE concrete production mode is the greatest, showing that although energy and labor are consumed and social economic resources are increased in the processes of sorting, crushing, transportation, collection, and treatment of waste concrete, the CE concrete production mode is becoming more and more sustainable with the integration and upgrading of the construction waste treatment industry chain and as the level of construction technology and quality control of green concrete continues to improve.

[Place Figure 8 here]

4.4 Prediction of sustainability direction

In the emergy ternary diagram, comprehensive analyses of the sensitivity and sustainability lines of concrete production systems can predict the future development direction of the system. R and N sensitivity lines are shown in Figure 9. Based on the current development situation, there are two possible development directions of the concrete production mode. One is from the upper part to the lower part along the sensitivity line of non-renewable resources; the other is from the lower part to the upper part along the sensitivity line of renewable resources. ESI gradually increases to ESI>1.

[Place Figure 9 here]

If the concrete production mode develops along the first path, the renewable resources of the system will contribute less and less to the concrete production system. With a decrease of the proportion of local renewable resources, the demand for non-renewable resources of the system increases, and the pressure on the environment caused by the concrete production process increases. Restricted by the limitation of local renewable resources during a specific period of time and the reduction of over-utilization of local non-renewable resources, the sustainability of system development is weakened.

The second development path of the concrete production mode is to maintain the current proportion of non-renewable resources and socio-economic emergy inputs, while improving the emergy ratio of renewable resources. Along with this development, it is necessary to improve the recycling capacity of concrete production waste, promote the implementation of green concrete production modes through investment of funds and technology, and adopt economical methods to reduce the loss of non-renewable resources, thereby reducing the cost of non-renewable resources in the production process of the system. The social and economic emergy inputs and renewable resource utilization ratio of the CE concrete production mode increases synchronously. With a decrease of the proportion of non-renewable resources, the ELR decreases, the emergy output rate of production process increases, and the sustainability of the system development increases. Obviously, the second development path of concrete production modes is the sustainable development mode that should be chosen.

5. Conclusion

In this paper, compare the traditional concrete production mode with the green concrete production mode (FAC, RAC and CE concrete production mode) by using the emergy index and emergy ternary diagram. It is shown that a large number of industrial waste (fly ash) is fully digested, urban construction waste is treated as recycled aggregate, and various wastes are recycled, in the green concrete production process. Green concrete is more and more applied in engineering construction, which can effectively solve the problems of construction waste and industrial waste dump, land pollution and so on. It can save raw material resources, land, energy consumption and protect the ecological environment.

Green concrete production is a complex and dynamic industrial ecosystem, with a variety of unit types of input and output. When using the emergy analysis method to analyze the benefit of the green concrete production system, the input and output values of the whole system should be considered, as well as the emergy distribution among the production factors in the production mode. The ternary diagram of emergy analysis directly reflects the resource allocation of the system. With the aid of the auxiliary lines of emergy ternary diagram analysis, the relationship between the emergy utilization ratio and indicators of the system can be analyzed, and the sustainability of the existing production system can be evaluated comprehensively.

However, there are some limitations in this study. The green concrete production model studied in this paper is based on FAC, RAC and CE concrete production modes. The results of the study are not applicable to green concrete production models not mentioned in this paper. Moreover, the UEV in this paper is cited from different sources, which increases the uncertainty of the research results. With the increasing application of emergy accounting in the evaluation of production modes in the future, more basic data is needed to establish a unified and time-efficient UEV standard system.

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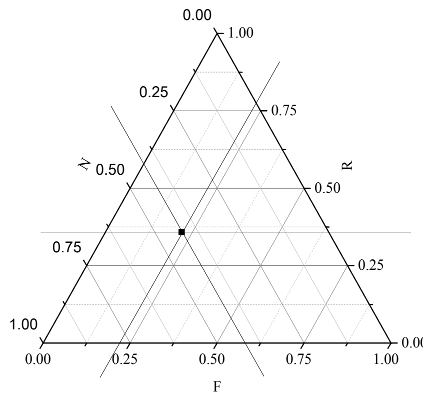
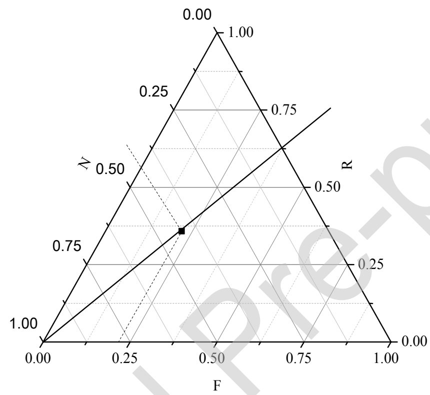
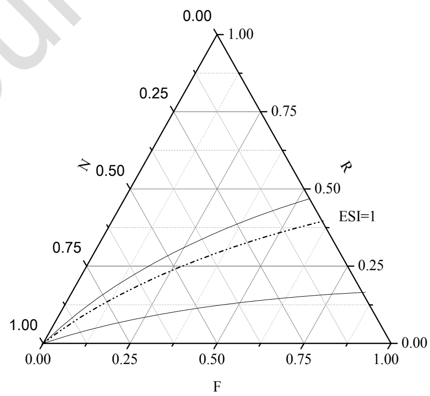
Figure



(a) Resource flow line



(b) Sensitivity line



(c) Sustainability line

Figure 1. The auxiliary lines of emergy ternary diagram

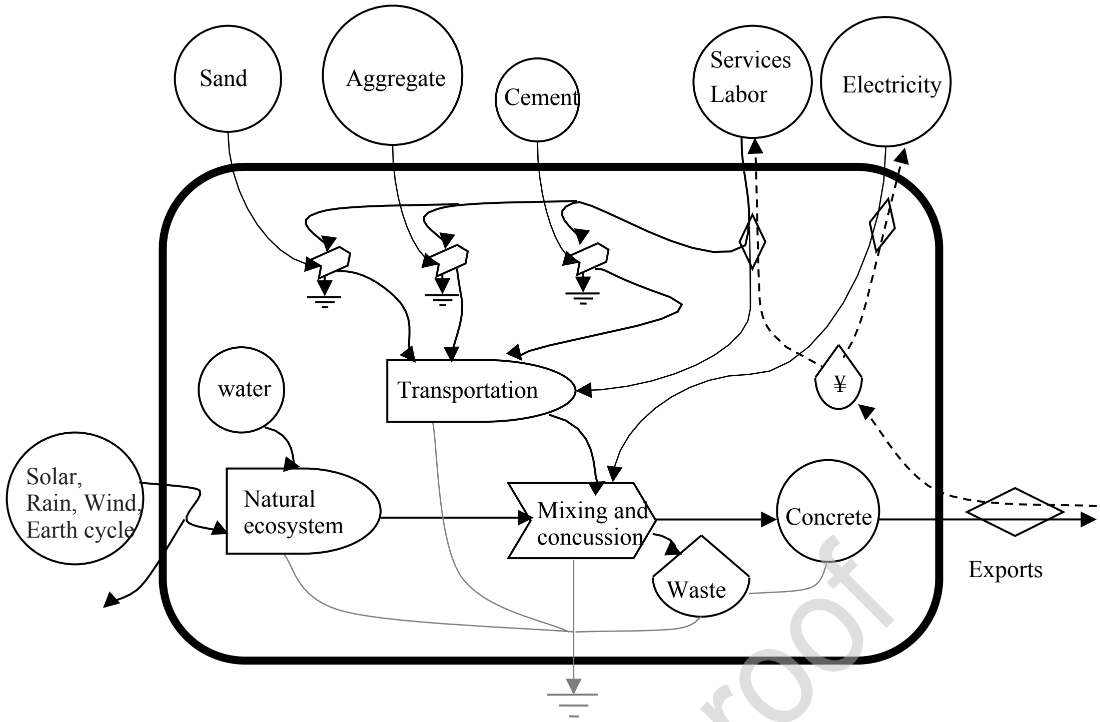


Figure 2 Emergy flow of traditional concrete production

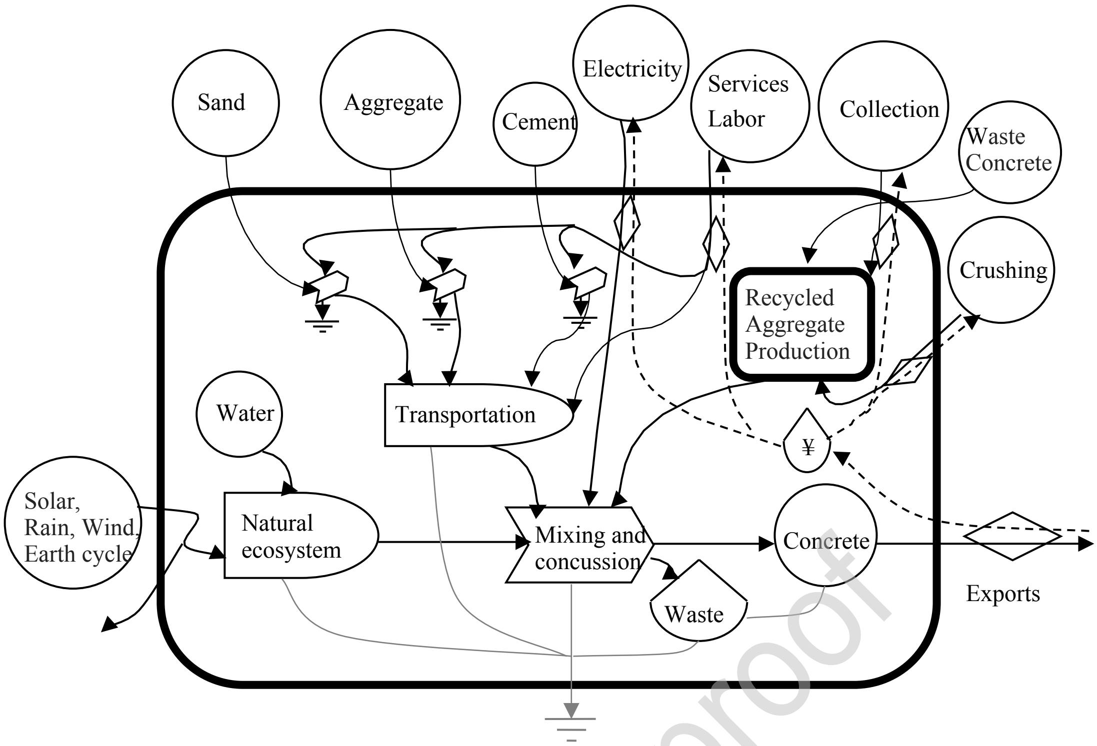


Figure 3 Emergy flow of recycled aggregate concrete (RAC) production

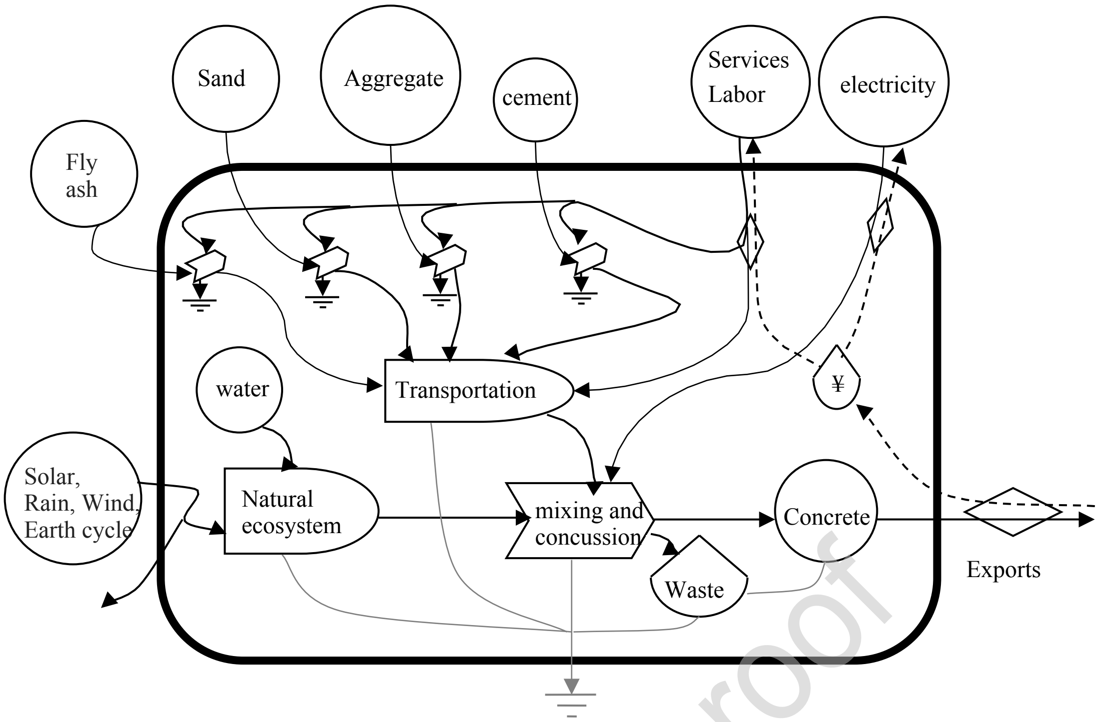


Figure 4 Emergy flow of fly ash concrete (FAC) production

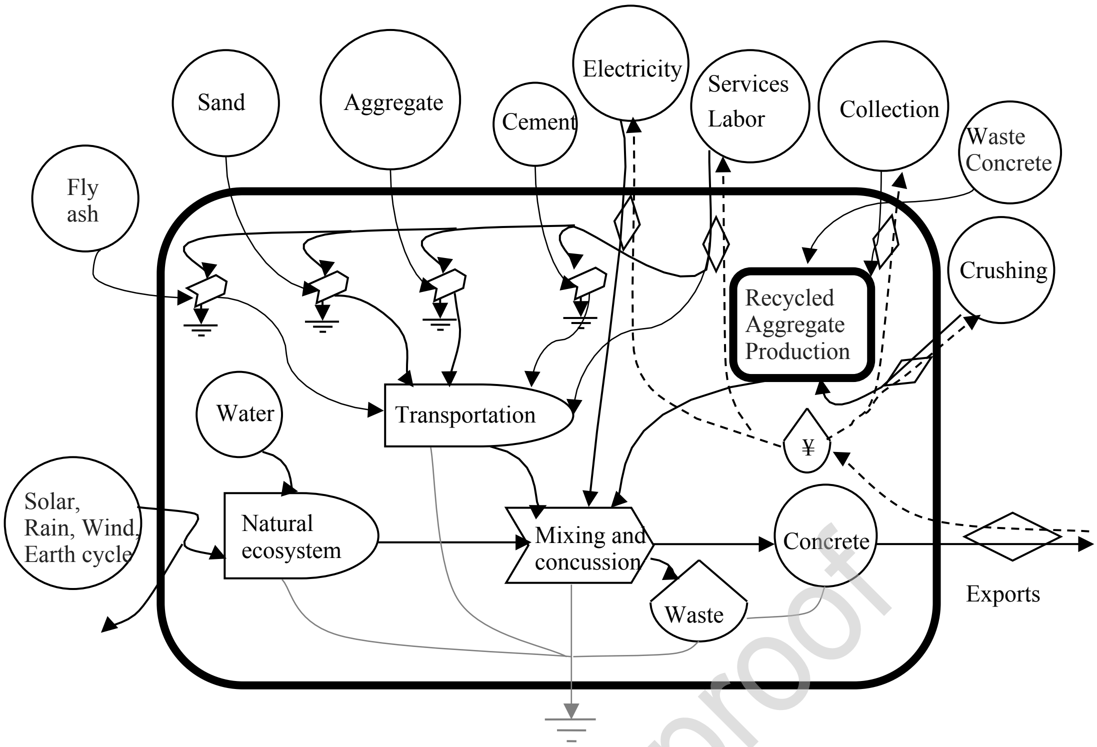


Figure 5 Emergy flow of circular economy (CE) mode of concrete production

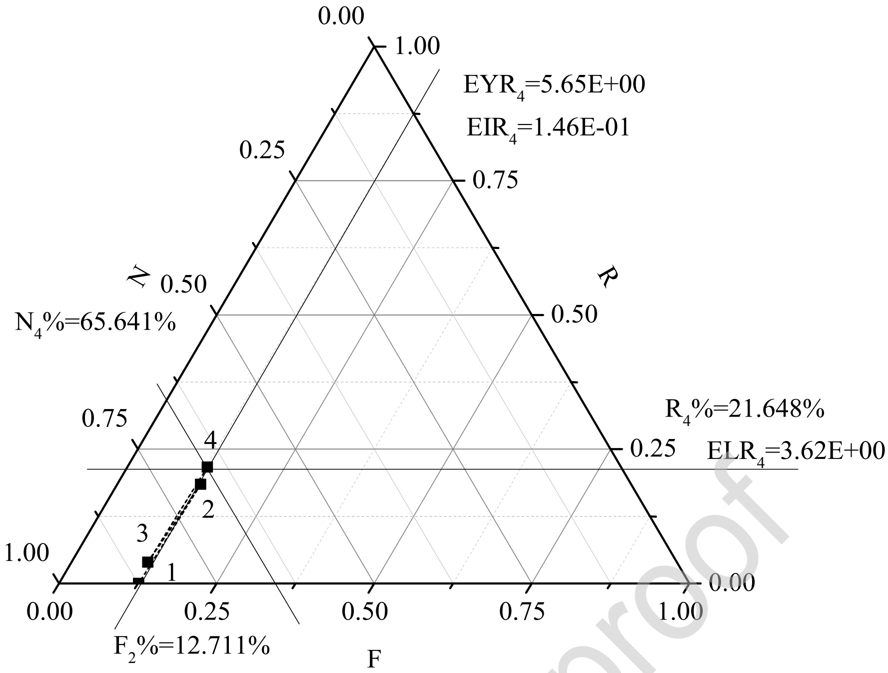


Figure 6 Resource flow lines of concrete production mode

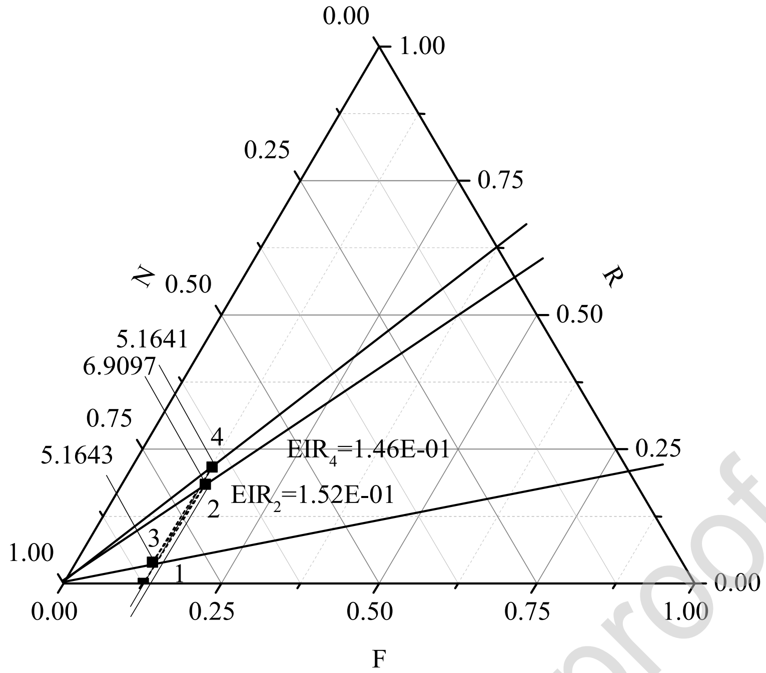


Figure 7 Sensitivity lines of concrete production mode

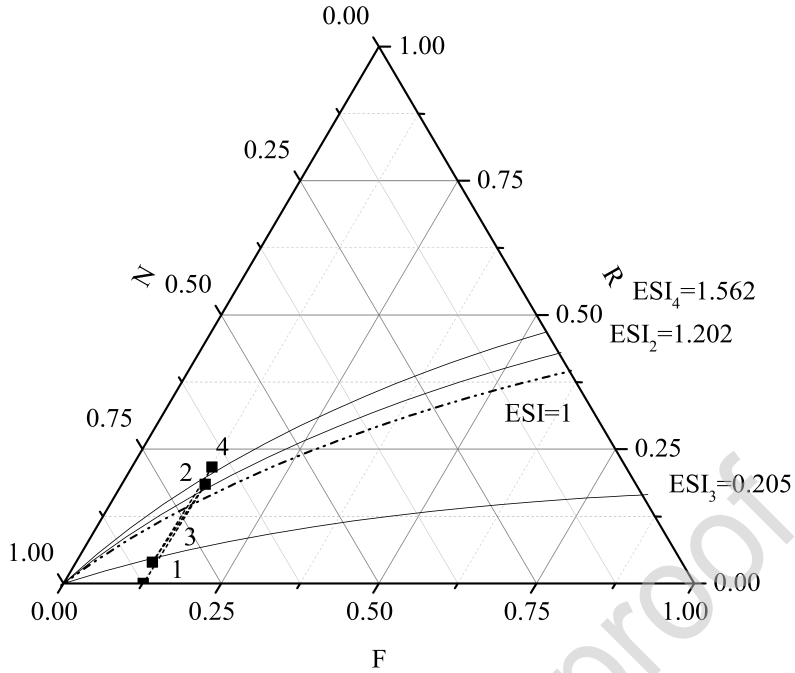


Figure 8 Sustainability lines of concrete production mode

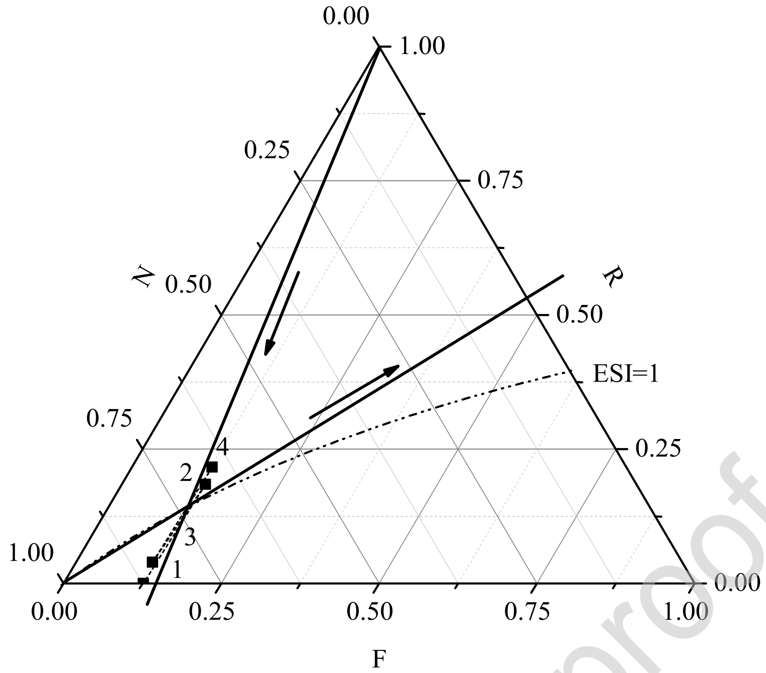


Figure 9 Forecast of sustainable development direction of green concrete

Table

Table 1 Emergy inputs and outputs of traditional concrete production

Raw materials	Input or output	Unit	UEV (Sej/ Unit)	Reference	Energy (Sej)
Renewable Resources (R)					
Water	1.75E+08	g	1.26E+06	Brown et al. (2012)	2.21E+14
Non-renewable resource (N)					
Cement	2.91E+08	g	1.73E+09	Brown and Arding (1991)	5.03E+17
Sand	6.23E+08	g	2.46E+09	Brown and Buranakarn (2003)	1.53E+18
Gravel	9.44E+08	g	2.46E+09	Brown and Buranakarn (2003)	2.32E+18
Social and economic input (F)					
Machining	1.08E+06	j	9.21E+09	Pulselli et al. (2008)	9.95E+15
Electricity	2.65E+10	j	1.59E+05	Brown and Ulgiati (2001)	4.21E+15
Transportation	7.41E+05	t×m	7.61E+11	Brown and Buranakarn (2003)	5.64E+17
Service and Labor	4.89E+05	$	1.06E+11	Lou and Ulgiati (2013)	5.18E+16
Emergy of Products(Y)					
Concrete output (year)	1.79E+09	g	1.81E+09	Pulselli et al. (2008)	3.24E+18

Table 2 Emergy of inputs and outputs of recycled aggregate concrete (RAC) production

Raw materials	Input or output	Unit	UEV (Sej/ Unit)	Reference	Energy (Sej)
Renewable Resources (R)					
Water	1.75E+08	g	1.26E+06	Brown et al. (2012)	2.21E+14
Recycled aggregate	3.77E+08	g	2.46E+09	Brown and Buranakarn (2003)	9.27E+17
Non-renewable resource (N)					
Cement	2.91E+08	g	1.73E+09	Brown and Arding (1991)	5.03E+17
Sand	6.23E+08	g	2.46E+09	Brown and Buranakarn (2003)	1.53E+18
Gravel	5.68E+08	g	2.46E+09	Brown and Buranakarn (2003)	1.40E+18
Social and economic input (F)					
Collection	1.71E+06	j	9.21E+09	Pulselli et al. (2008)	1.57E+16
Crushing	2.07E+06	j	9.21E+09	Pulselli et al. (2008)	1.91E+16
Machining	1.08E+06	j	9.21E+09	Pulselli et al. (2008)	9.95E+15
Electricity	2.65E+10	j	1.59E+05	Brown and Ulgiati (2001)	4.21E+15
Transportation	7.41E+05	t×m	7.61E+11	Brown and Buranakarn (2003)	5.64E+17
Service and Labor	4.89E+05	$	1.06E+11	Lou and Ulgiati (2013)	5.18E+16
Emergy of Products(Y)					
Concrete output (year)	1.95E+09	g	1.81E+09	Pulselli et al. (2008)	3.53E+18

Table 3 Emergy of input and output of fly ash concrete (FAC) production

Raw materials	Input or output	Unit	UEV (Sej/ Unit)	Reference	Energy (Sej)
Renewable Resources (R)					
Water	1.75E+08	g	1.26E+06	Brown et al. (2012)	2.21E+14
Fly ash	1.22E+07	g	1.68E+09	Pulselli et al. (2007)	2.05E+16
Non-renewable resource (N)					
Cement	2.04E+08	g	1.73E+09	Brown and Arding (1991)	5.03E+17
Sand	6.23E+08	g	2.46E+09	Brown and Buranakarn (2003)	1.53E+18
Gravel	9.44E+08	g	2.46E+09	Brown and Buranakarn (2003)	2.32E+18
Social and economic input (F)					
Machining	1.08E+06	j	9.21E+09	Pulselli et al. (2008)	9.95E+15
Electricity	2.65E+10	j	1.59E+05	Brown and Ulgiati (2001)	4.21E+15
Transportation	7.41E+05	t×m	7.61E+11	Brown and Buranakarn (2003)	5.64E+17
Service and Labor	4.89E+05	$	1.06E+11	Lou and Ulgiati (2013)	5.18E+16
Emergy of Products(Y)					
Concrete output (year)	1.73E+09	g	1.81E+09	Pulselli et al. (2008)	3.13E+18

Table 4 Emergy of input and output of circular economy (CE) concrete production

Raw materials	Input or output	Unit	UEV (Sej/ Unit)	Reference	Energy (Sej)
Renewable Resources (R)					
Water	1.75E+08	g	1.26E+06	Brown et al. (2012)	2.21E+14
Recycled aggregate	3.77E+08	g	2.46E+09	Brown and Buranakarn (2003)	9.27E+17
Fly ash	1.22E+08	g	1.68E+09	Pulselli et al. (2007)	2.05E+17
Non-renewable resource (N)					
Cement	2.04E+08	g	1.73E+09	Brown and Arding (1991)	5.03E+17
Sand	6.23E+08	g	2.46E+09	Brown and Buranakarn (2003)	1.53E+18
Gravel	5.68E+08	g	2.46E+09	Brown and Buranakarn (2003)	1.40E+18
Social and economic input (F)					
Collection	1.71E+06	j	9.21E+09	Pulselli et al. (2008)	1.57E+16
Crushing	2.07E+06	j	9.21E+09	Pulselli et al. (2008)	1.91E+16
Machining	1.08E+06	j	9.21E+09	Pulselli et al. (2008)	9.95E+15
Electricity	2.65E+10	j	1.59E+05	Brown and Ulgiati (2001)	4.21E+15
Transportation	7.41E+05	t×m	7.61E+11	Brown and Buranakarn (2003)	5.64E+17
Service and Labor	4.89E+05	$	1.06E+11	Lou and Ulgiati (2013)	5.18E+16
Emergy of Products(Y)					
Concrete output (year)	2.08E+09	g	1.81E+09	Pulselli et al. (2008)	3.76E+18

Table 5 Emergy indicators of concrete production modes

Emergy indicators	traditional concrete (1)	Green Concrete Production		
		RAC (2)	FAC (3)	CE concrete (4)
R%	0.004%	18.459%	3.961%	21.648%
N%	87.354%	68.313%	83.898%	65.641%
F%	12.642%	13.228%	12.142%	12.711%
Y	3.23E+18	3.53E+18	3.13E+18	3.76E+18
ELR	2.50E+04	4.42E+00	2.42E+01	3.62E+00
EYR	5.13E+00	5.31E+00	4.97E+00	5.65E+00
EIR	1.45E-01	1.52E-01	1.38E-01	1.46E-01
ESI	2.05E-04	1.20E+00	2.05E-01	1.56E+00

Declaration of Interest Statement

No conflict of interest exits in the submission of this manuscript, and manuscript is approved by all authors for publication. I would like to declare on behalf of my co-authors that the work described was original research that has not been published previously, and not under consideration for publication elsewhere, in whole or in part. All the authors listed have approved the manuscript that is enclosed.

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Highlights：

- A visually expressive research tool is proposed for green concrete production mode evaluation.
- The sustainability of concrete production modes is comprehensively analyzed by emergy assessment index.
- Traditional concrete production mode is compared with green concrete production modes.
- Circular economy (CE) mode of green concrete production is the most environmentally friendly and sustainable concrete production mode by contrastive analysis.