THE NEW CENTURY OF CONCRETE TECHNOLOGIES
– INTRODUCTION OF ENVIRONMENTAL AXIS –

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SUMMARY

Concrete is one of the most important materials employed in public works and building construction projects. It means that we have utilized a tremendous amount of concrete and we will have to continue to use it. On the other hand, sustainable development has become more and more important. The human race is steadily transitioning its socioeconomic system in an effort to solve its resource, energy and environmental problems. It is obvious that the concrete industry also have to introduce environmental axis into its technologies. This paper discusses environmental aspects of concrete, introduces "JSCE Recommendation of Environmental Performance Verification for Concrete Structures (Draft)" and ISO XXXXX on "Environmental Management for Concrete and Concrete Structures" as the standardization of environmental aspects in concrete and concrete structures and represents the examples of environmental design based on the JSCE Recommendation.

***Keywords**: Concrete; concrete structures; environmental aspects; environmental design; standardization.*

INTRODUCTION

Mankind has been facing serious problems such as resource depletion and global warming caused by the consumption of fossil fuels. These represent, however, only the beginning of such problems. With land covering only 30% of the earth's surface and currently being occupied by over 6 billion people (half of them in cities), and with the population expected to reach 9 billion within 50 years, further problems are expected. Furthermore, the consumption of resources and energies in developing countries, including China, which account for some 70% of the world's population, is predicted to exponentially increase. Depletion of resources is not limited to minerals and fossil fuels; it also encompasses the depletion of food and water supplies.

The Limits to Growth [Meadows, Meadows, Randers and Behrens III 1972], a revelatory book that warned about the finiteness of resources, was published 35 years ago, but its

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message was not taken seriously back then. However, subsequent aggressive economic activities in industrialized nations gave rise to various environmental problems, spawning movements that respond to such problems. The Brundtland Report [The World Commission on Environment and Development 1987], published in 1987 by the UN World Commission on Environment and Development, introduced the concept of "sustainable development" - development that does not interfere with the needs of future generations. It was a milestone report in which it clearly proposed the direction humans should take. The report also touched on the issue of global warming, but the concept is now recognized as a foundation of resource- and energy-saving technology development in many fields. At the Earth Summit held in 1992 in Rio de Janeiro, the importance of sustainable development that aims to balance the needs of environmental conservation and economic development was reconfirmed, and the UN Framework Convention on Climate Change (UNFCCC) was signed by member states before taking effect in 1994. This development led to the adoption of the Kyoto Protocol, with aims to cut greenhouse gas emissions, at the third session of the Conference of the Parties (COP3) to the UNFCCC held in 1997 in Kyoto. The Kyoto Protocol, which took effect in 2005, covers the five-year period between 2008 and 2012, and post-COP3 deliberations are now under way. The Kyoto Protocol introduced the "Kyoto Mechanism," which includes the clean development mechanism (CDM) and emission trading, to promote the reduction of greenhouse gas emissions in developing countries and other regions. As of October 4, 2006, 334 CDM projects had been registered, aggregately reducing some 88-million tons of greenhouse gases in terms of CO_2. Also, 76 projects are now applying for CDM registration. In Europe, an EU directive set CO_2 emission caps on approximately 12,000 plants and facilities, which has helped spread emission-right trading in the region.

Concrete is one of the most important materials employed in public works and building construction projects. It means that we have utilized a tremendous amount of concrete and also will have to continue to use it. As mentioned above, on the other hand, sustainable development has become more and more important. The human race is steadily transitioning its socioeconomic system in an effort to solve its resource, energy and environmental problems. It is obvious that the concrete industry also have to introduce environmental axis into its technologies.

This paper discusses environmental aspects of concrete, introduces "JSCE Recommendation of Environmental Performance Verification for Concrete Structures (Draft)" and ISO XXXXX on "Environmental Management for Concrete and Concrete Structures" as the standardization of environmental aspects in concrete and concrete structures and represents the examples of environmental design based on the JSCE Recommendation.

ENVIRONMENTAL ASPECTS OF CONCRETE

Aggregate

It is said that, of the approximately 26 billion tons of annual material flow throughout the world, aggregate used as a construction material accounts for some 20 billion tons [Brown 2001]. In other words, natural sand, gravel and crushed stone exist most abundantly in the natural world, thus these materials are most frequently used for infrastructure development.

Although the aggregate situation varies by country and region, the replacement of natural aggregate with crushed stone aggregate has progressed in recent years due to environmental restrictions. It is believed that this has also led to changes in the quality of aggregate, which greatly affects the quality and durability of concrete. Crushed stone aggregate usually has sharp edges, thereby increasing the water content of concrete, and the energy used for the production of crushed stone has an adverse impact on the environment. Moreover, the development of quarries is also causing environmental problems.

In recent years it has been said that infrastructure development has matured in Japan. While the number of national highways and bridges 50 years or older managed by nation and local governments in Japan was 8,191 in 2005, it is expected to increase to 63,494 by 2025 [Ministry of Land, Infrastructure and Transport 2005]. Reconstruction of structures is also increasing in urban areas. According to an estimate by the Development Bank of Japan [Development Bank of Japan 2002], the total amount of concrete masses to be generated in 2025 is estimated to be 210 million tons, which is a twofold increase of the 112 million tons generated in 2005. These amounts are extremely high, considering that the total concrete production for Japan in 2005 was approximately 285 million tons. While most concrete masses have been used as base course materials, their demand is expected to decrease dramatically. Since the use of these as recycled aggregate is crucial considering the pressure on waste disposal sites and the preservation of aggregate resources, the development of technologies for recycled aggregate production is being promoted.

Technologies for recycled aggregate production in Japan include the heating and rubbing [Tateyashiki, Okamoto, Nishimura and Kuroda 2000], eccentric-shaft rotor [Yanagibashi, Yonezawa, Kamiyama & Inoue 1999] and mechanical grinding [Yoda, Shintani, Takahashi & Yanagase 2004] methods. In the heating and rubbing method, concrete masses are heated at 300℃ and the cement paste content is weakened to remove mortar and cement paste from the aggregate. Figure 1 shows an overview of a recycled aggregate production system using this method. Figure 2 illustrates the recycled coarse and fine aggregate produced by the system. While the production of recycled aggregate generated a large amount of fine powder, it also indicated the possibility of using fine powder like this as a substitute solidification material for the deep mixing stabilization method (soil cement walls) [Uchiyama, Kuroda & Hashida 2003]. In the eccentric-shaft rotor method, crushed concrete lumps are passed downward between an outer cylinder and an inner cylinder that eccentrically rotates at a high speed to separate it into coarse aggregate and mortar through a grinding effect. Figure 3 presents an overview of a recycled aggregate production system using this method. Mechanical grinding is a method used to produce coarse and fine aggregate by separating a drum into small sections with partitions, loading the drum with iron balls for grinding and rotating the partitions. Figure 4 shows an overview of the recycled aggregate production system using this method. The coarse aggregate produced by these methods has been used for actual construction projects.

In Japan, JIS A 5021 [Japanese Standards Association 2005] was established in 2005 as a standard for high-quality recycled aggregate H for concrete, which is produced through advanced processing, including crushing, grinding and classifying, of concrete masses generated in the demolition of structures. Recycled aggregate H must have physical properties satisfying the requirements listed in Table 1. There are also upper limits for the amounts of deleterious substances contained in recycled aggregate H, as shown in Table 2. JIS A 5023 has also been established as a standard for recycled concrete using low-quality recycled aggregate L. This type of concrete includes backfilling, filling and leveling concrete, and the use of Type

B blended cement and admixture is required as a measure against alkali-silica reactivity.

Production of recycled aggregate usually involves greater energy use compared with that of virgin aggregate, thus leading to greater environmental impacts. While finding ways to deal with these environmental impacts as an external cost is a major issue, it would be ideal to absorb this cost in the entire production/use system of recycled aggregate. As shown in Figure 5, Kuroda et al. [2004] established an on-site concrete resource recycling system from this standpoint, and proved that CO_2 emissions from the system were lower than those in which it was used as a conventional base course material. This was achieved by reducing the amount of transported material and the use of fine powder as a substitute solidification material for ground improvement. Yanagibashi [2004] studied CO_2 emissions in the cases of use of recycled aggregate for base course material made of concrete masses, use of recycled coarse aggregate for concrete and recycled sand for base course and backfill materials, and use of recycled coarse aggregate for concrete and the remaining amount for cement clinker. The paper concluded that the use of recycled aggregate was an environmentally friendly method that could contribute to the preservation of natural aggregate since CO_2 emissions were nearly identical.

Iron and steel slag is also used as aggregate. In 2005, 25,747,000 tons of blast-furnace slag and 14,897,000 tons of steelmaking (converter and electric-furnace) slag were generated in Japan [Nippon Slag Association 2005]. Of these, blast-furnace slag was primarily used as aggregate for concrete, and its amount was 3,158,000 tons.

While fly ash has been used as a substitute admixture for cement, the idea of using this as fine aggregate has emerged in recent years [Shikoku Chapter of Japan Society of Civil Engineers 2003]. Considering the worldwide increase in fly ash production expected in the future, it is desirable to design a mix that integrates substitutes for cement and fine aggregate.

In recent years, melting treatment of waste and sewage sludge has become common in Japan due to pressures on waste disposal site and problems related to dioxin and heavy metals. Molten slag is generated as a residue after melting treatment. In 2004, 144 waste and 18 sewage sludge melting treatment facilities were in operation throughout Japan, producing 480,000 and 44,000 tons of molten slag, respectively. Waste molten slag production is estimated to reach as high as 2.7 million tons in the future. Melting treatment was also commenced in 2005 for 600,000 tons of illegally dumped industrial waste in Teshima, Kagawa Prefecture [Takatsuki 2003]. Approximately 300,000 tons of molten slag is to be produced for 10 years, and the prefecture government has decided to use the entire amount as aggregate for concrete. Basic studies on the application of municipal solid waste and Teshima molten slag to concrete have been conducted [Matsuka, Sakai, Nakamura & Kusanagi 2006a], [Matsuka, Sakai, Nishigori, Yokoyama, Nishimoto & Onodera 2006b]. Molten slag is characterized by low water-retentivity since it is vitreous. When it is used in large amounts, bleeding increases and leads to a decease of the strength of concrete and, in the case of reinforced concrete, a decrease in the bond of reinforcing bars to concrete. The permissible replacement ratio of molten slag for fine aggregate thus varies according to the performance required for concrete. It is also necessary to pay attention to aluminum, which is a metal contained in molten slag, since it may cause expansion and deterioration of concrete as it reacts with the alkali of cement and generates hydrogen. In Japan, JIS A 5031 [Japanese Standards Association 2006] was established for molten slag aggregate for concrete. Table 3 lists the physical properties of molten slag required by this standard.

Cement

Cement is the most important basic material for infrastructure development. There are two aspects of cement production and its relation to the environment – CO_2 emissions and the use of waste as a raw material and fuel. Japan's cement production, including blended cement and export, has amounted to more than 800 million tons in the last 10 years. The world's cement production is thought to be approximately 2 billion tons at present. Figure 6 shows the cement demand predicted by Humphreys et al. [2002] According to this prediction, production is expected to reach approximately 4 billion tons 30 years from now. Figure 7 displays the CO_2 emission unit of cement production in each country/region. Based on the mean value 0.87(kg-CO_2/kg-Cement) of these, CO_2 emissions from cement production totaling 4 billion tons is estimated to be approximately 3.5 billion tons, which is 2.7 times as high as Japan's current total CO_2 emissions (approx. 1.3 billion tons). Also, based on the lowest CO_2 emission unit of Japan (0.73), the world's CO_2 emissions are expected to reach approximately 2.9 billion tons 30 years from now. This means that the world's cement-originated CO_2 emissions can be reduced by approximately 8% through the use of Japan's cement production technology.

Nearly 30 million tons of waste and byproducts are currently used as raw materials and fuels for cement production in Japan. Such raw materials include blast-furnace slag, fly ash and sewage sludge, and fuels include waste tires and plastic. Figure 8 illustrates the changes in cement production and use of waste and byproducts in Japan. It can be seen that the use of waste and byproducts is steadily increasing while cement production is decreasing. The cement industry is setting a target value of 400 kg/t-cement for 2010. Figure 9 shows an international comparison of energy consumption per ton of cement clinker, in which Japan displays incomparably high energy efficiency. It can be seen from this that Japan has exceptional cement production technology. This means that CO_2 emissions associated with the construction of concrete structures is being reduced as a consequence.

Admixtures

It can be said that basic technologies have already been established for the use of admixtures in concrete [Japan Society of Civil Engineers 1996]
[Japan Society of Civil Engineers 1999]. Admixtures have been used for concrete for the effective use of industrial byproducts and improvement in concrete properties through their utilization. In recent years, however, their importance in the reduction of environmental impacts has also attracted attention.

As shown in Figure 10, approximately 67% of blast-furnace slag was used for blast-furnace cement in Japan in 2005. This means that the performance of blast-furnace slag is used in the most rational manner. Figure 11 presents the breakdown of the use of coal ash (9,792,000 tons) in Japan in 2004 [Japan Coal Energy Center 2006]. Of the 70% used in the field of cement, the majority was used as a raw material for cement production. Although the amount of fly ash that can be used for concrete is approximately 20% of the total production of coal ash, its use as an admixture for concrete is only about 1%. This situation is not appropriate considering the excellent performance of fly ash as an admixture. Approximately 10% of the coal ash produced in Japan is currently disposed of in landfills.

Figure 12 shows the estimated volumes of admixture production in the world in 2002 and 2020 [Jahren 2003]. In particular, the production volumes of fly ash and blast-furnace slag are expected to increase 1.7 and 3 times, respectively. By effectively using these increased volumes of admixtures, it will become possible to reduce environmental impacts caused by the future increase in concrete demand.

STANDARDIZATION OF ENVIRONMENTAL ASPECTS IN CONCRETE AND CONCRETE STRUCTURES

JSCE Recommendation of Environmental Performance Verification for Concrete Structures

The Japan Society of Civil Engineers (JSCE) published the Recommendation of Environmental Performance Verification for Concrete Structures (draft) [Japan Society of Civil Engineers 2005]. This Recommendation (draft) provides general principles of consideration concerning environmentality when conducting design, construction, use, maintenance/management, dismantling, disposal and reuse after dismantling of a concrete structure. Its purpose is to extend the application of performance verification concept on safety, serviceability and durability of concrete structures to the "environment." The Recommendation (draft) consists of chapters on general rules, environmentality, evaluation and verification of environmental performance, inspection and records. The followings are listed as items that must be taken into account when considering the environmental aspects of concrete structures:

(1) Greenhouse gas, air contaminants, resources/energy, waste
(2) Water and soil contaminants
(3) Noise/vibration
(4) Others

The followings are also provided as methods to be used for evaluation of environmental performance:

(1) LCA method for evaluation of the emission of greenhouse gasses and air contaminants, consumption of resources/energy, waste generation, etc.
(2) Appropriate testing and measurement methods for identification and quantitative evaluation of the substances causing water and soil contamination
(3) Direct measurements, reliable prediction methods or a combination of both for evaluation of noise, vibration, etc.
(4) Others

The Recommendation (draft) also gives examples of basic environmental impact units and integration factors necessary for evaluation of environmental performance related to design, construction and other aspects of concrete structures.

The verification of environmental performance is the act of confirming that the value of performance retained by a structure (R) is larger (or smaller) than the set value (S) based on the performance requirements for the structure concerning the environmental aspect subject to the verification. For example, verification of CO_2 emissions can be passed if the calculated value of CO_2 associated with an actual structure is smaller than the absolute value of CO_2 emissions set as the performance requirement (or the value based on the reduction rate from the standard value). In the case of the use of a byproduct, the minimum amount that must be used is set as the performance requirement, which is satisfied if the amount used for a structure is larger than this value. While environmental performance requirements may include legal regulations, demands of the owners and intentions of the designer, they are referred to as the regulation value, limit value and target value, respectively, in the Recommendation (draft).

When considering the environmental performance by comparative design, the designer is not necessarily required to set a target value, and "verification" will become unnecessary if the decision-maker selects an appropriate one from the environmental performance evaluation results of several designs.

ISO XXXXX (Environmental Management for Concrete and Concrete Structures)

As for environment-related international standards, there is the ISO 14000 series. In ISO 14040, the principle and framework of environmental management (life cycle assessment) are provided. This standard is for general products, and its life cycle assessment is composed of the purpose, definition of the scope, inventory analysis, impact assessment and interpretation. A standard for buildings and civil engineering structures is ISO 15686-6 [2004]. This standard is for the consideration of environmental impacts in service life planning of structures, and provides general procedures for environmental impact assessment of design options. Also, ISO/TC59/SC17/WG3 is currently examining the draft of environmental product declaration standards for buildings and civil engineering structures [ISO/FDIS 21930 2006]. The purpose of this draft is to make environmental product declarations (EPD) on environmental impacts, resource use, discharge of waste and other matters by looking at buildings and civil engineering structures as "products." Although the objects of these two ISO standards (drafts) are identical, their ideas and methods are different.

As mentioned above, although there are several ISO Standards on environmental aspects, it can be said that most of them have a very broad scope and therefore it is difficult to apply for practical objects. Considering such a situation, ISO/TC71 decided to form a Working Group on environmental aspects in 2005 to examine the possibility of environmental standards for concrete and concrete structures. The Working Group has concluded that we need to make the standards for concrete and concrete structures in order to provide the procedures for considering environmental impacts. The ISO/TC71 Plenary meeting in 2007 resolved the establishment of SC8 on Environmental Management for Concrete and Concrete Structures. The following ISO Standards will be developed:

ISO XXXXX: Environmental Management for Concrete and Concrete Structures -

- Part 1: General principles for environmental consideration
- Part 2: Preparation of inventory data and system boundaries
- Part 3: Concrete production
- Part 4: Execution of concrete structures
- Part 5: Maintenance of concrete structures
- Part 6: Demolishment and reuse of concrete structures
- Part 7: Recycling of concrete
- Part 8: Labels and declarations
- Part 9: Environmental design of concrete structures

EXAMPLES OF ENVIRONMENTAL DESIGN BASED ON THE JSCE RECOMMENDATION [SAKAI 2005]

RC Rigid Frame Viaduct

Railway crossings cause traffic congestion and have large impacts on the regional environment and traffic safety problems. To solve these problems, it is necessary to introduce overhead crossings at railway facilities. Construction of railway overpasses in urban residential area where crossings are used may involve a variety of restrictions in many cases. In such a situation, RC rigid frame viaduct is considered. A rigid frame bridge usually has footing beams at the joints between piles and columns to absorb unevenness in the bearing capacity of piles and ensure seismic performance.

As the environmental performance requirements of a rigid frame viaduct, the followings are set:

(1) 20% reduction of CO_2 emission
(2) Limiting noise, vibration, air contamination to certain values

In order to satisfy the above environmental performance requirements, a structural type that ensures the required seismic performance by increasing the bearing capacity of piles and reinforcing the joints between piles and columns with steel tubes is introduced as shown in Figure 13.

The CO_2 emission from materials, transport and construction was calculated for the structural types with and without footing beams. Figure 14 shows the results. By adopting a structure without footing beams, CO_2 emissions could be reduced by approximately 28% in all, compared with the conventional RC rigid frame viaduct. The environmental requirement was verified: the environmental performance requirement regarding CO_2, S, was less than the retained performance, R. It can be also said that the selection of this structural type reduces surrounding environmental influences such as traffic congestion, noise, vibration and air contamination that accompany construction work. For the calculation of CO_2 emission, the JSCE unit-based substance emission data base was used.

Ultra High-Strength Steel Fiber-Reinforced Concrete (UFC) Pedestrian Bridge

There is a plan to renew reinforced concrete pedestrian bridge across a river. Considering the span of the bridge, approximately 50m, three-span prestressed concrete bridge is conventionally one option. However, according to the required performance regarding environmental impact reduction, which is twenty percent reduction of CO_2 emission compared with conventional structure, a new technology needs to be introduced. Ultra high-strength steel fiber-reinforced concrete (UFC) is used.

Ultra high-strength steel fiber-reinforced concrete (UFC) can dramatically reduce the dead weight of a structure because of its excellent strength characteristics. The foundation can be thinner as a result and may also lead to the reduction of construction costs. The maintenance cost can also be reduced because of the excellent durability of UFC. Table 4 and Figure 15 show the mix proportions and the bending behavior of UFC. Steel fiber of 0.2 mm in diameter, 15 mm in length and 2800N/mm2 in tensile strength was mixed. UFC was used to construct a 50.2-meter-long 2.4-meter-wide outer-cable prestressed bridge with an unreinforced box-type closed section with variable web height (upper slab thickness = 5 cm, web thickness = 8 cm). Figures. 16 and 17 show the cross section and general view of this bridge, respectively. The dead weight of the bridge was 560 kN. Precast blocks consisting of three types of segment blocks were manufactured at a precast concrete product plant. They were cured twice. Sheet curing was first conducted in an open-air environment, followed by 48-hour steam curing at 90°C. If this bridge was to be designed as a three-span, PC simple slab bridge (hereinafter referred to simply as “PC bridge”), which is thought to be the most rational for its conditions, its dead weight would be 2,780 kN, approximately 5 times that of the UFC bridge. Figure 18 shows a general view of the hypothetical PC bridge.

The CO_2 emissions from the production of the materials, steel forms, and UFC beams or pre-tension hollow beams, the transport and the construction were calculated for UFC and PC bridges. Fig.A2.5 shows the results. By utilizing UFC, CO_2 emissions could be reduced by approximately 25% in all, compared with conventional PC bridge. The environmental requirement was verified, ie. the environmental performance requirement regarding CO_2, S, was less than the retained performance, R. For the calculation of CO_2 emission, the JSCE unit-based substance emission data base was used.

CONCLUDING REMARKS

The IPCC Fourth Assessment Report says the followings as global warming and its cause:

(1) Warming of the climate system is unequivocal.

(2) Most of the observed increase in globally averaged temperatures since mid-20th Century is very likely due to the observed increase in anthropogenic greenhouse Gas concentration.

Construction and concrete industry have been utilizing a tremendous amount of resources and energy. Therefore, they have a responsibility to reduce environmental impacts in their activities. For the concrete industry to contribute to the sustainable development of mankind, it is necessary to promote technical development for further reduction of environmental impacts. To promote this, it will be necessary to introduce environmental design systems based on environmental performance, develop environmental performance evaluation tools and construct systems for their actual application.

The most effective way to solve environmental problems would be to impose strictly-enforced legal restrictions within a national or international framework. However, this will cause conflict of various interests, so it would be difficult to set specific targets. However, the cost of environmental problems will ultimately have to be paid by humans. What we must do now is to create a good circle where a reasonable system aiming to reduce environmental impacts is first established and the development of related technologies is promoted to make the system function. The standardizations described in this paper are basically not legally binding, but environmental impacts can be reduced by effectively using these systems. The JSCE environmental guidelines, which specifically target concrete structures, should highly be rated in which they clearly established a framework to reduce the environmental impacts related to concrete. Also, the work for standardization on environmental management for concrete and concrete structures, which the ISO/TC71 will soon start, are extremely important for the concrete industry to meet its social responsibilities for the environment.

Since environmental consideration generally lead to an increase in cost and the reduction of environmental impacts was not a design requirement in the design of structures, environmental impacts have been thought of as negative externality. The comprehensive evaluation bidding system is currently attracting attention in Japan as a system for enabling internalization of negative externality. The bidding system enable absorption of the cost increases resulting from environmental consideration. It is desirable to actively use this system in the future.

The IPCC Fourth Report also says that sustainable development can reduce vulnerability to climate change. It is obvious that the concrete sector also has to consider the reduction of environmental impacts in their technologies towards the sustainable development of human beings. We are now in the beginning of the new century of concrete technologies.

REFERENCES

Meadows, D. H., Meadows, D. I., Randers J. and Behrens III, W. W. (1972) "Limit of Growth," the Club of Rome.

The World Commission on Environment and Development (1987) "Our Common Future," Oxford University Press.

Brown, L. R. (2001) "Eco-Economy," Earth Policy Institute.

Ministry of Land, Infrastructure and Transport (2005) "White paper on land, infrastructure and transport in Japan."

Development Bank of Japan (2002) "Urban renewal and resource recycling: For the creation of a resource recycling society," Research Report No.28.

Tateyashiki, H., Okamoto, M., Nishimura, Y., and Kuroda, Y. (2000) "Experimental studies on production of high quality recycle aggregate from demolished concrete," Proc. of the Japan Concrete Institute, Vol.22 No.2: 1099-1104 (in Japanese).

Yanagibashi, K., Yonezawa, T., Kamiyama, Y., and Inoue, T. (1999) "Study on high quality recycle aggregates," Proc. of the Japan Concrete Institute, Vol.21 No.2: 205-210 (in Japanese).

Yoda, K., Shintani, A., Takahashi, I., and Yanagase, S. (2004) "Quality of recycles coarse and fine aggregates produced by mechanical grinding," Proc. of the Japan Concrete Institute, Vol.26 No.1: 1627-1532 (in Japanese).

Uchiyama, S., Kuroda, Y., and Hashida, H. (2003) "Deep mixing stabilization using concrete powder from recycled aggregate production by heating and rubbing," The Foundation Engineering & Equipment, July: 62-65 (in Japanese).

Japan Standards Association (JIS A 5021) (2005) "Recycled aggregate for concrete-class H (in Japanese)."

Kuroda, Y., Hashida, H., Nachi, Y., Yamazaki, N., and Miyachi, Y. (2004) "A closed-loop concrete system on a construction site," Technical Research Report of Shimizu Corporation 79: 1-10 (in Japanese).

Yanagibashi, K. (2004) “Inventory and analysis on a process of recycling aggregate for concrete, Construction Materials, Vol.13 No.1: 38-45 (in Japanese).

Nippon Slag Association (2005) “Annual Statistics Report of Iron and Steel Slag,” http://www.slag.jp/e/index.htm.

Shikoku Chapter of Japan Society of Civil Engineers (2003) “Recommendation on execution of concrete using fly ash as a fine aggregate substitute (draft) (in Japanese).”

Takatsuki, H. (2003) “The Teshima Island industrial waste case and its process towards resolution,” Special feature: Conference Report, Journal of Material Cycles and Waste Management, 5: 26-30.

Matsuka, T., Sakai, K., Nakamura, T., and Kusanagi, S. (2006) “Flexure and shear behavior of reinforced concrete beams using molten slag from industrial waste,” Journal of Materials, Concrete structures and Pavements, No.809 V-70: 131-145 (in Japanese).

Matsuka, T., Sakai, K., Nishigori, W., Yokoyama, T., Nishimoto, Y., and Onodera, S. (2006) “Effect of rubbing-reformation in application of various molten slag to concrete,” Journal of Materials, Concrete structures and Pavements, No.809 V-70: 147-158 (in Japanese).

Japanese Standards Association (JIS A 5031) (2006) “Melt-solidified slag aggregate for concrete derived from municipal solid waste and sewage sludge (in Japanese).”

Humphreys, K. and Mahasenan, M. (2002) “Toward a sustainable cement industry,” Climatic change sub-study 8, World Business Council for Sustainable Development.

Japan Society of Civil Engineers (1996) “Recommendation on execution of concrete using blast furnace slag,” Concrete Library 86 (in Japanese).

Japan Society of Civil Engineers (1999) “Recommendation on execution of concrete using fly ash (draft),” Concrete Library 94 (in Japanese).

Japan Coal Energy Center (2006) “Annual Report 2005/06,” http://www.jcoal.or.jp/news_en/news_en.html#061005-1

Jahren, P. (2003) “What are the options? The CO_2 case,” STF22A03610 Report, SINTEF.

Japan Society of Civil Engineers (2005) “Recommendation of environmental performance verification for concrete structures (draft),” JSCE Guidelines for Concrete No.7.

ISO 15686-6 (2004) “Buildings and constructed assets – Service life planning – Part 6: Procedures for considering environmental impacts,”

ISO/FDIS 21930 (2007) “Sustainability in building construction – Environmental declaration of building products”

Sakai, K. (2005) “Environmental design of concrete structures,” Journal of Advanced Concrete Technology, Vol. 3, No.1, 17-28.

Table 1. Physical properties requirements for recycled aggregate H

Items	Coarse aggregate	Fine aggregate
Oven-dry density, g/cm^3	not less than 2.5	not less than 2.5
Water absorption, %	not more than 3.0	not more than 3.0
Abrasion, %	not more than 35	NA
Solid volume percentage for shape determination, %	not less than 55	not less than 53
Amount of material passing test sieve 75μm, %	not more than 1.0	not more than 7.0
Chloride ion content	not more than 0.04	

Table 2. Limits of amount of deleterious substances for recycled aggregate

Category	Deleterious substances	Limits (mass %)
A	Tile, Brick, Ceramics, Asphalt	2.0
B	Glass	0.5
C	Plaster	0.1
D	Inorganic substances other than plaster	0.5
E	Plastics	0.5
F	Wood, Paper, Asphalt	0.1
Total		3.0

Table 3. Physical properties requirements for molten slag aggregates

Molten slag / Items	Coarse aggregate	Fine aggregate
Oven-dry density, g/cm^3	not less than 2.5	not less than 2.5
Water absorption, %	not more than 3.0	not more than 3.0
Soundness, %	not less than 12	not less than 10
Solid volume percentage for shape determination, %	not less than 55	not less than 53
Amount of material passing test sieve 75μm, %	not more than 1.0	not more than 7.0

Table 4. Mix proportion of UFC

Water	Cement	Grain (quartz, sand, etc.)	Steel fibers	Super-plasticizer
180	818	1479	157	24

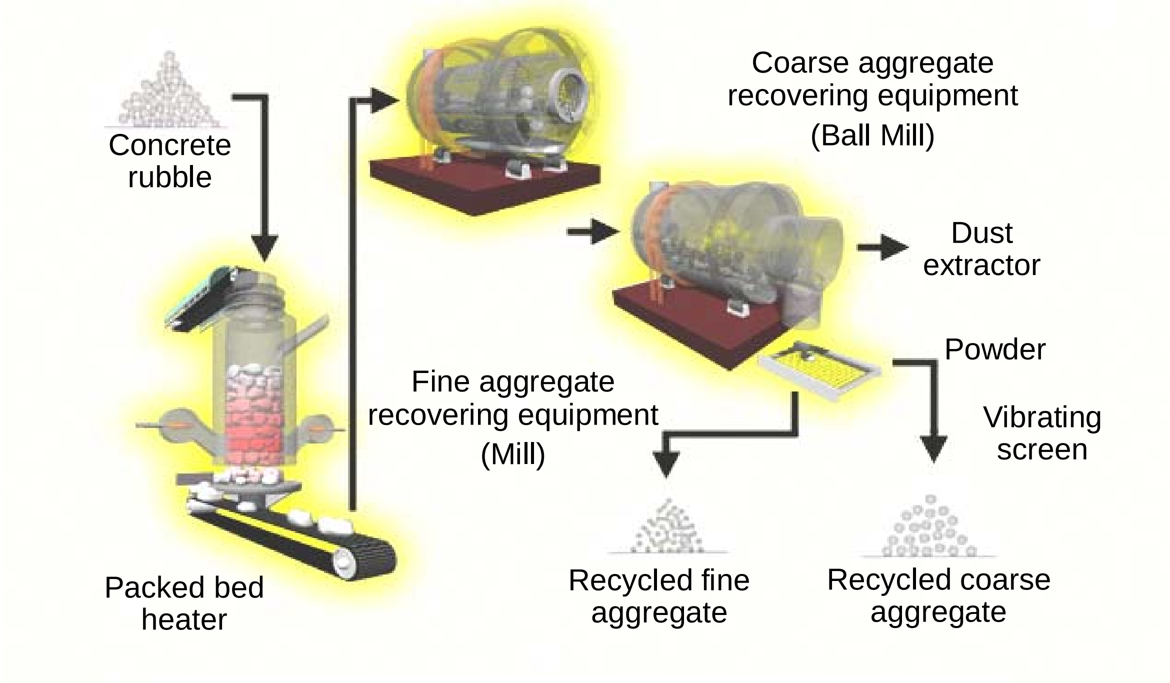


Figure 1. Production technology of recycled aggregate (heating

Figure 2. Recycled aggregates by heating and rubbing method

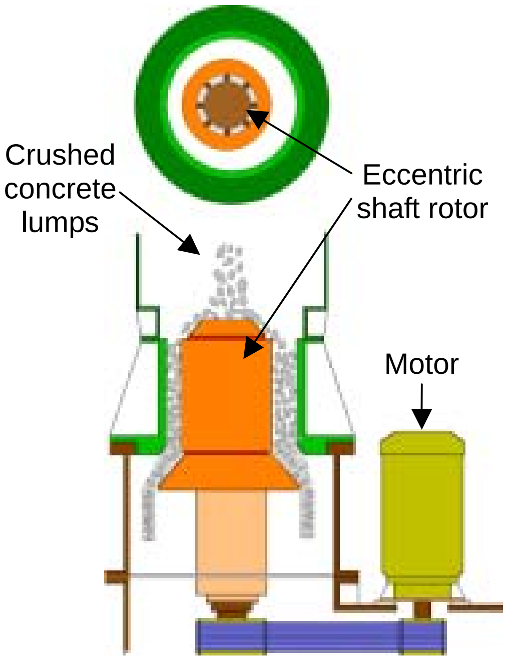


Figure 3. Production technology of recycled aggregate (eccentric-shaft rotor method)

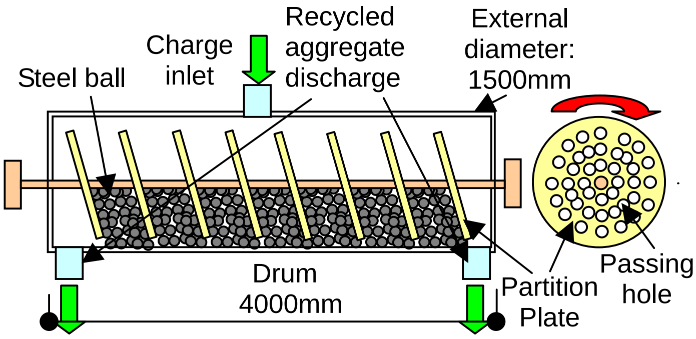


Figure 4. Production technology of recycled aggregate (mechanical grinding method)

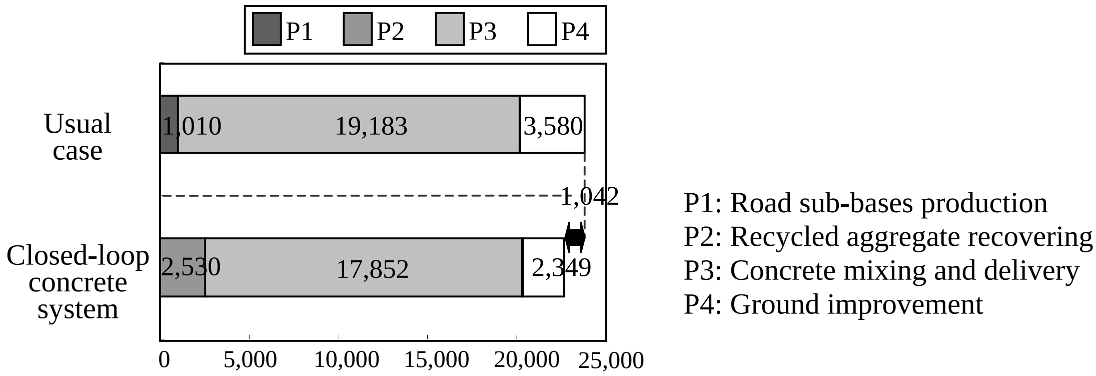


Figure 5. CO_2 emission in usual and closed-looped concrete recycle systems

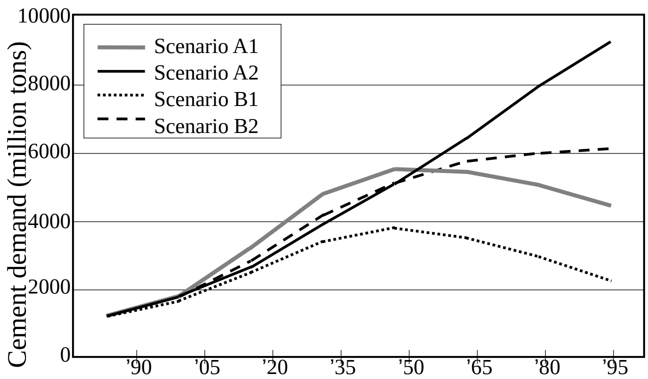


Figure 6. Estimated cement demand.

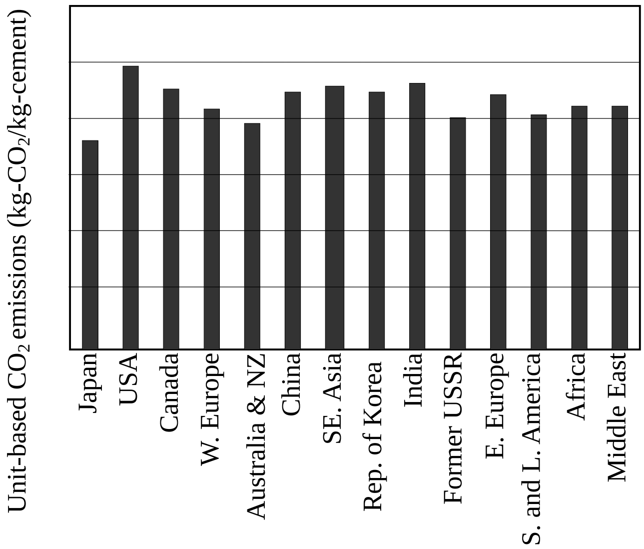


Figure 7. Unit-based CO_2 emission in cement manufactures

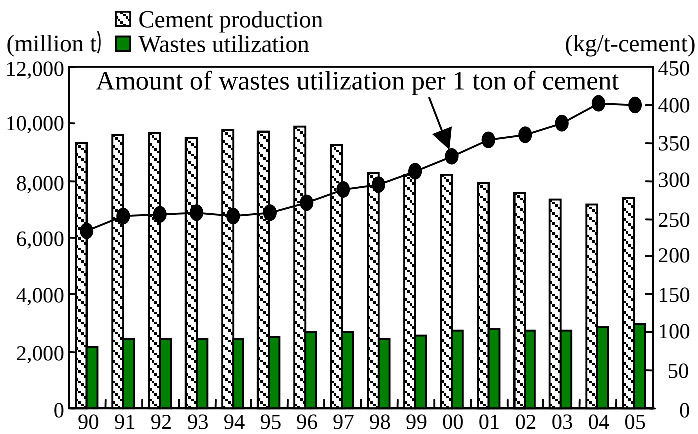


Figure 8. Amount of wastes utilization for cement production in Japan.

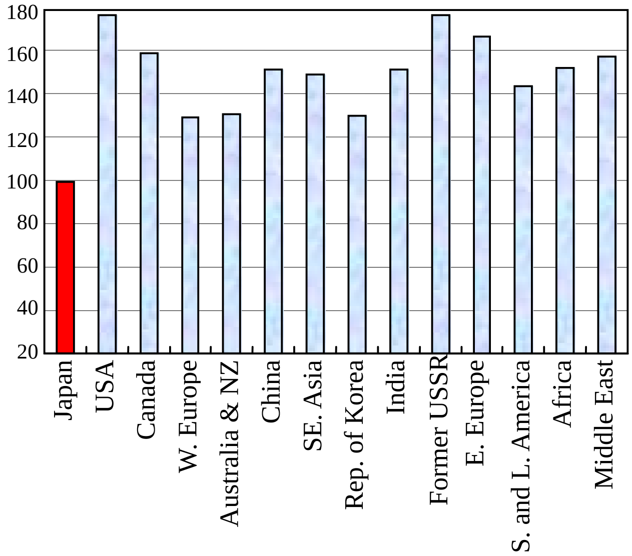


Figure 9. International comparison of energy consumption in cement-clinker production

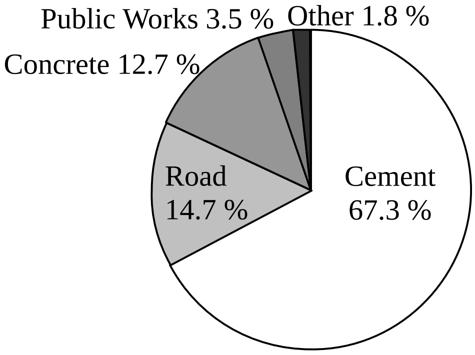


Figure 10. Utilization of blast furnace slag in Japan

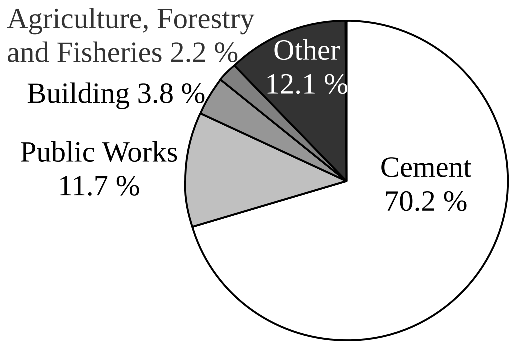


Figure 11. Utilization of fly ash in Japan

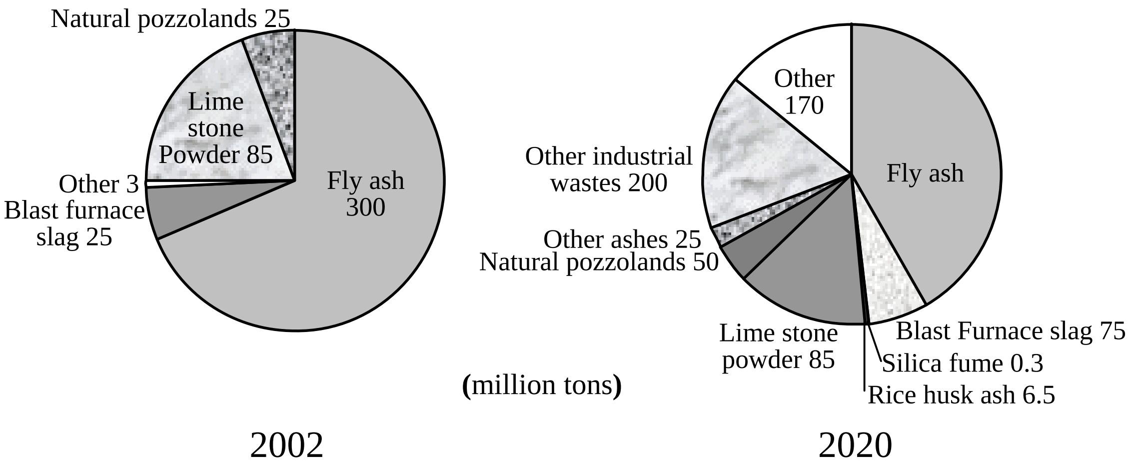
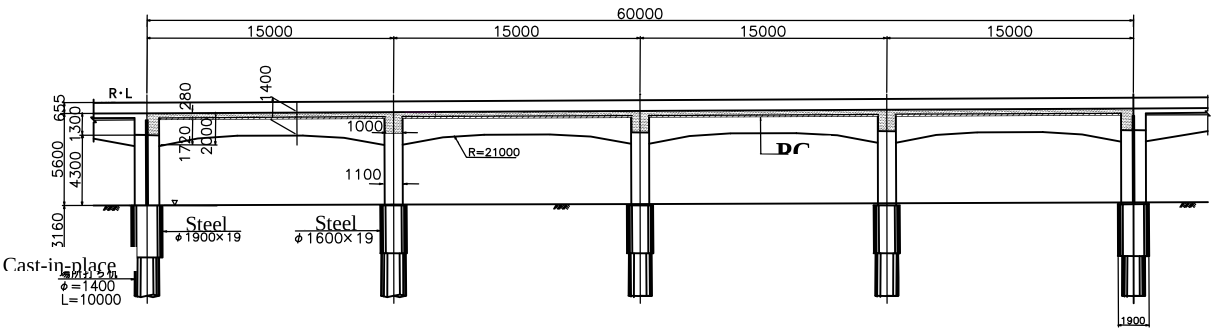
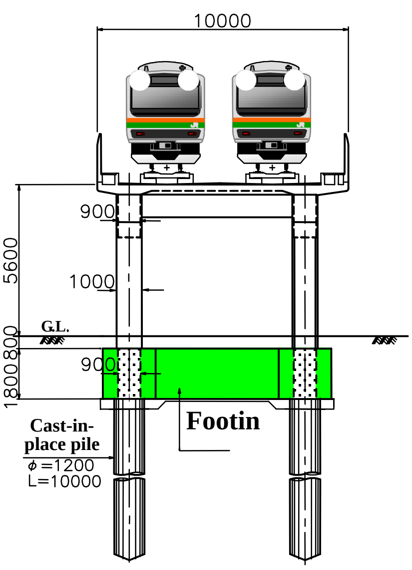


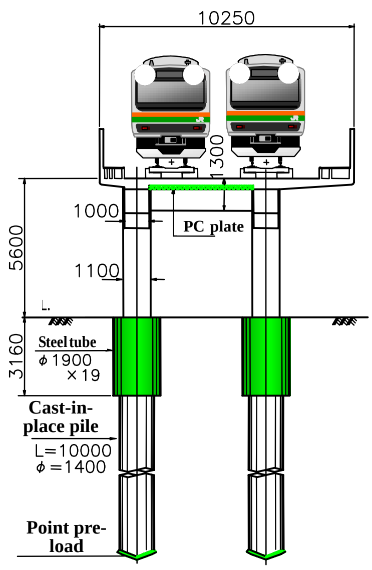
Figure 12. Estimated world admixture mineral production



(a) General view (no footing beam)



(b) Sectional view (with footing beam)



(c) Sectional view (without footing beam)

Figure 13. RC rigid frame viaduct

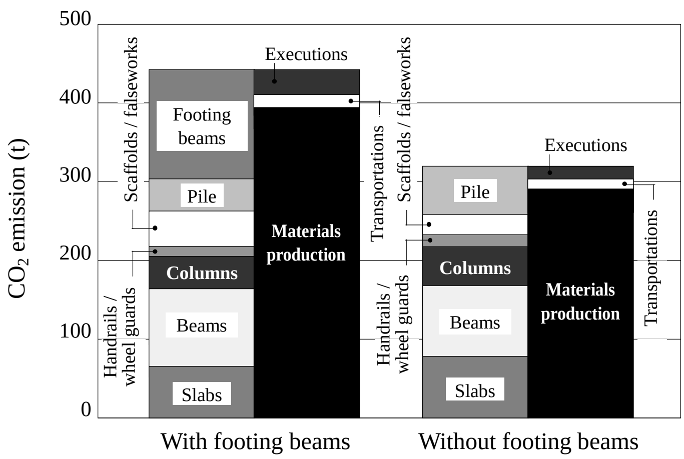


Figure 14. CO2 emissions of RC rigid frame viaduct

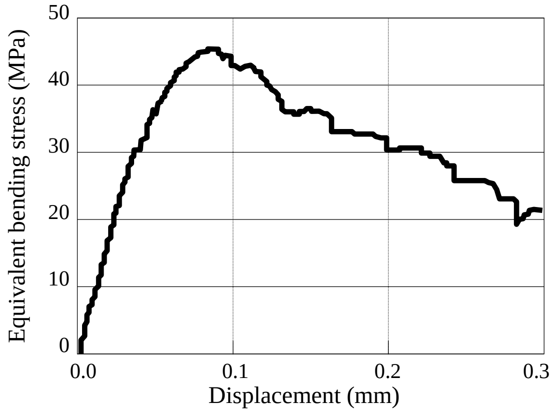


Figure 15. Flexural behavior of ultra high-strength steel-fiber reinforced concrete

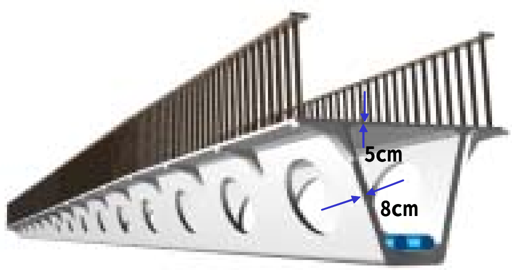


Figure 16. Sectional view of UFC

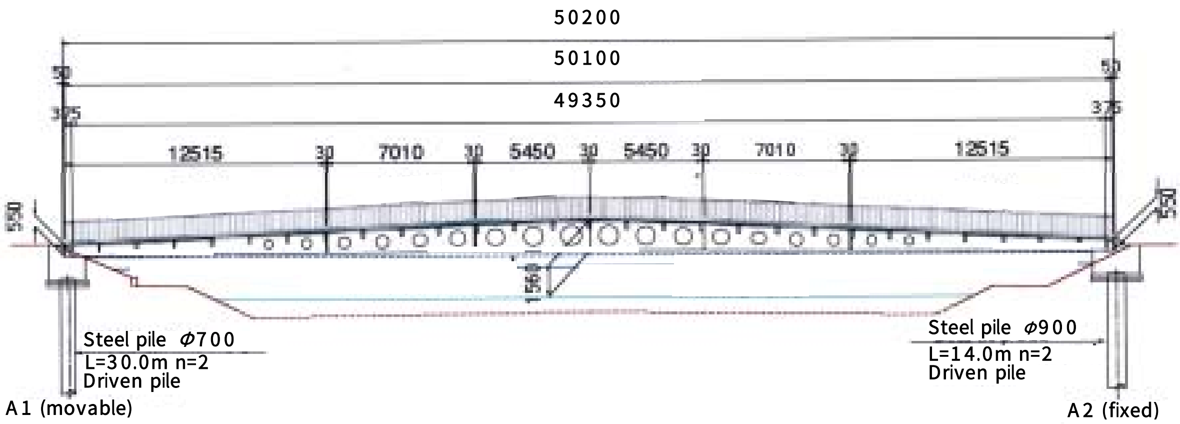


Figure 17. General view of UFC bridge

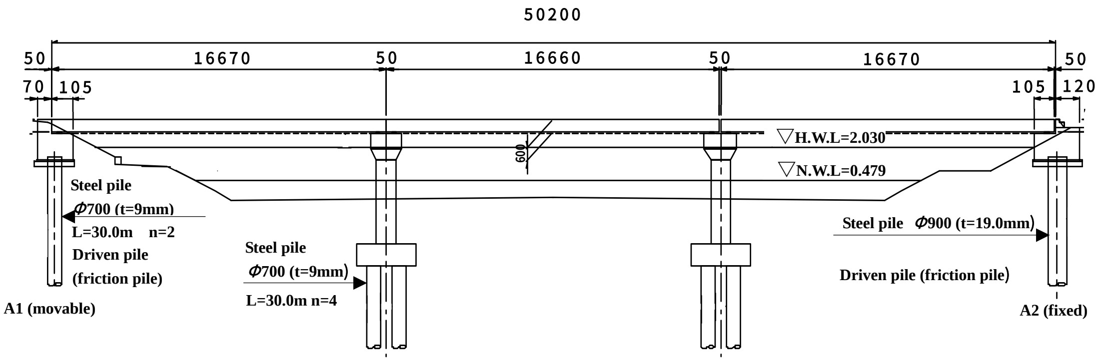


Figure 18. General view of hypothetical PC bridge

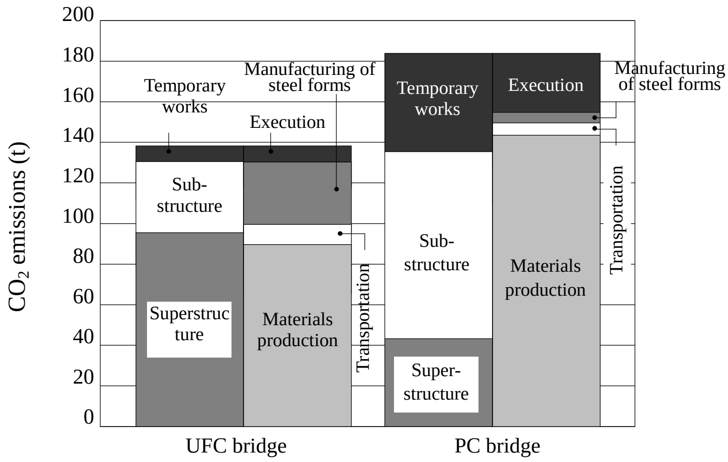


Figure 19. CO_2 emissions of UFC and PC bridges