High-slag Cement and Structures for Substantial Reduction of Energy and CO_2

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ABSTRACT

A technology System for substantial reduction of energy and CO_2 by cement production and for reduction of CO_2 foot print of concrete structures was studied. The study resulted in a proposal of a technology system named Energy CO_2 Minimum (ECM) Cement Concrete System. The system consists of a newly developed high-slag cement (ECM cement) and structures for which the cement with weakness of rapid carbonation can be used. In this paper outline of the study to produce the above concept is presented. Then the present situation of the research and development work on the system is introduced; the introduction includes the cement, the concrete using the cement, the structural members using the concrete and the improved soil using the cement, which constitute the technology system.

Keywords. High-slag cement, CO_2, Concrete, Carbonation, Improved soil

INTRODUCTION

The CO_2 emission by cement production in Japan is approximately 3% of total Japanese CO_2 emission of 1.3 billion tons (2010). Fig.1 shows CO_2 foot print related to building construction and utilization (Murakami, 2010); 9% is for construction and 31% is for utilization. Thus 40% of national CO_2 has some relation to buildings. Cement and construction industries have crucial effects on Japanese CO_2 emission.

As shown in Fig.2, 20 to 30% of construction induced CO_2 is from concrete and nearly 100% of the concrete induced CO_2 is from cement. Reduction of CO_2 by cement production is important for both cement and construction industries.

It has been known that blast furnace slag, fly ash and the like are effective in reducing CO_2 emission by cement. Cements using such materials, however, tend to show low early age strength, high drying shrinkage and high carbonation rate. It is difficult to solve such problems by only cement industry. Reasonable way is to combine such cements with construction and structural technologies which enable using them.

This is the basic idea of the technology named Energy CO_2 Minimum (ECM) Cement Concrete System which is under development by the authors supported by NEDO (New Energy and Industrial Technology Organization, a Japanese Government Sector).

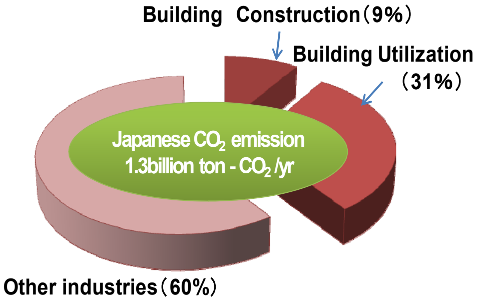


Figure 1. Effects of building related CO_2 on Japanese total CO_2

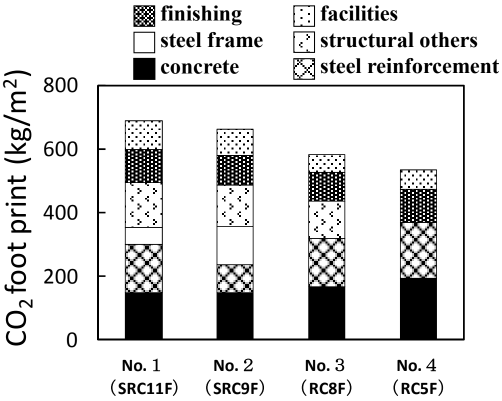


Figure 2. Effects of concrete related CO_2 on building construction induced CO_2

CONCEPT STUDY

CO_2 reduced cement

Table 1 shows a comparison of the materials and technologies that have potential capability of reducing energy and CO_2 of cement. High-slag cement with slag content of over 60% is obviously most effective in terms of expected energy and CO_2 reduction, resource limitation and cost effects. High-slag cement has good CO_2 reducing capability, but it has faults of rapid carbonation, low early age strength, high drying shrinkage and the like. Rapid carbonation is an essential fault in using the cement for building structures with thin cover thickness. If these problems are solved, the high-slag cement (ECM cement) can be used for the purpose of substantial reduction of energy and CO_2 by cement and CO_2 foot print of concrete structures.

Structures for the Cement

Structures appropriate for high-slag cement were studied in terms of carbonation.

Table 1 –Evaluation of energy and CO_2 reducing performances of cements and technologies

Cements and technologies	Expected reduction*(%)		Resource limitation in Japan	Cost effects*
	Energy	CO_2		
Conventional slag cement **	40-45	40-45	20～25millions tons slag	Slightly down
High – slag cement	60-70	60-70	20～25millions tons slag	Down
Fly ash cement	10-30	10-30	5～10millions tons fly ash	Slightly down
Mineral addition such as lime	5-20	5-20	(not limited)	Slightly down
Low temperature sintering process	5-10	—	—	Not clear

* compared with ordinary Portland cement **slag content of 40-45% in Japan

Some membres of RC (reinforced concrete) building structures in Japan have a thin cover thickness of 30 to 50mm, and life time is normally determined by carbonation. It is normally difficult to use such high-slag cement with rapid carbonation for buildings due to short expected life time. High-strength concrete, however, reduces carbonation substantially. Structures using such concrete are appropriate for ECM cement. RC structures with thick cover such as civil structures are also appropriate for ECM cement. In both cases durability design for carbonation is necessary. CFT (concrete filled tube) structures are free from carbonation, since the concrete in the tube is surrounded by outer steel tube. When cost effective CFT structure is developed, ECM cement can be used for the structure. Fig.3 shows a new CFT structure developed for ECM cement. The structure is a combination of CFT and reinforcing bars inside; cost performance is in between CFT and RC members.

RC piles are appropriate for ECM cement due to limited carbonation of concrete in ground. If performances of improved soil in terms of strength and ductility are increased, the improved soil can be used as a foundation for buildings. The improved soil foundation is also appropriate for ECM cement since they contain no steel reinforcements inside.

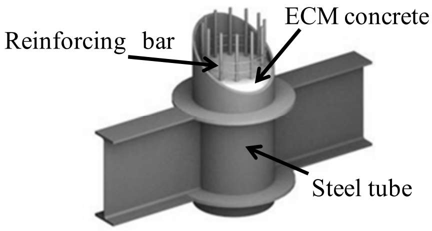


Figure 3 – A structure for ECM cement (CFTcombined with RC)

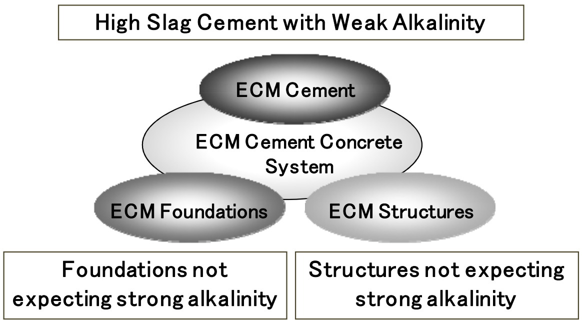


Figure 4 – Concept of ECM Cement Concrete System

Concept of ECM Cement Concrete System

When other weakness of high-slag cement such as low early age strength and high drying shrinkage is improved, and when the improved cement is combined with the structures mentioned above, the high-slag cement (ECM cement) can be used for building structures resulting in substantial reduction of CO_2 foot print of concrete structures. This combination of high-slag cement and structures appropriate for it is the concept of ECM Cement Concrete System as shown in Fig. 4.

DEVELOPMENT OF ECM CEMENT

Effects of activator on slag hydration are shown in Fig.5, when ordinary Portland cement (OPC) is used as an activator. The relation between slag hydration and OPC content is not simple,but the slag well hydrates when OPC content is in a range of 0.5 to 2.0% or more than 10%. Fig.6 shows development of slag hydration with time. The percentage of slag hydration becomes maximum value of around 30% when OPC content is 1% and 15%. The percentage is much smaller than the value known for ordinary Portland cement. This low hydration percentage will be a characteristic of slag cements.

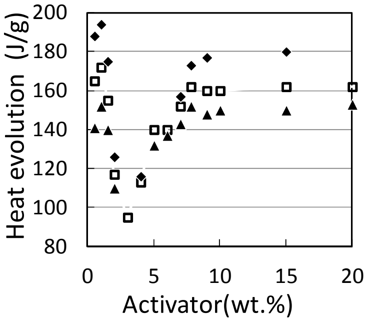


Figure 5 – Effects of activator(OPC) contents on cement hydration (1 week)

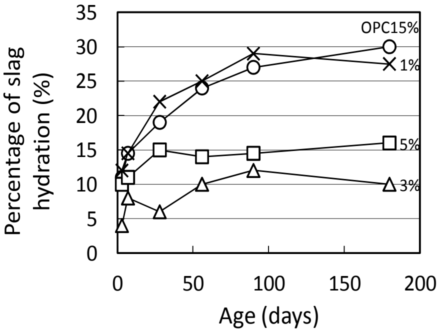


Figure 6– Hydration percentage of slag with time

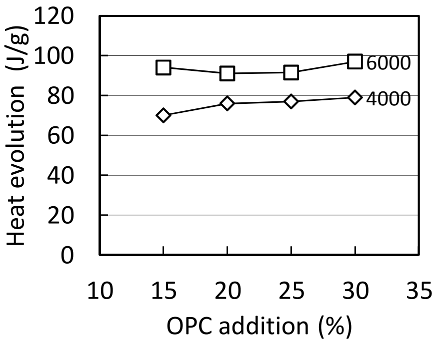


Figure 7– Effects of slag finess on cement hydration (24 hours)

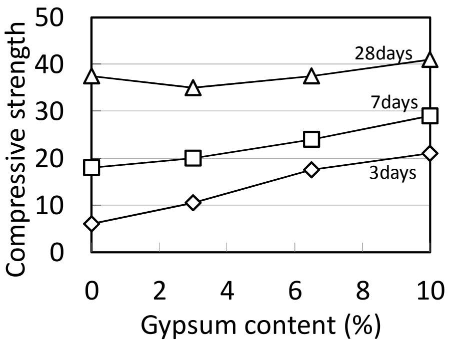
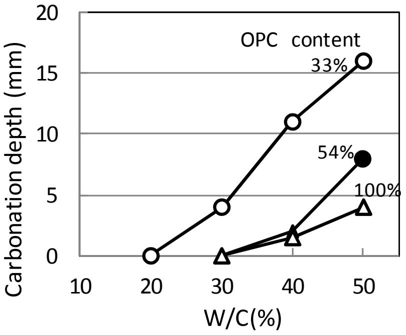


Figure 8 – Effects of anhydrous gypsum contents on compressive strength (W/C=50%)



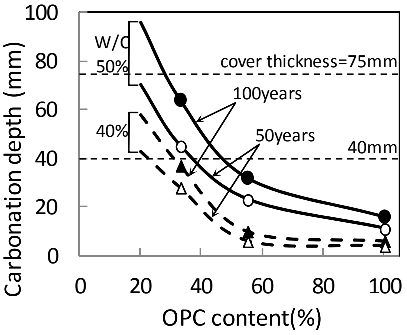


Figure 9– Accelerated carbonation of concretes with different OPC contents (91days, CO_2=5%,temperature=20℃,relative humidity=60%)

Figure 10 – Effects of OPC contents on estimated long term carbonation depths (temperature=20℃,relative humidity=60%)

Fig.7 shows effects of slag finess on the heat of hydration up to 24 hours after mixing. A slag with finess of 6000 cm^2/g shows higher heat evolution than a slag of 4000 cm^2/g, suggesting higher early age strength of slag cement by increasing finess value. Fig.8 shows effects of anhydrous gypsum content on the compressive strength of concretes. Higher early age strength is obtained with higher gypsum content.

Fig.9 shows carbonation development of concrete using cements with different OPC contents by accelerated carbonation tests (CO_2=5%). Fig.10 shows effects of OPC addition on estimated long term carbonation depth based on AIJ (Architectural Institute of Japan) method (AIJ, 2004) using the results in Fig.9. Carbonation rate is obviously influenced by OPC addition and W/C; the lower the OPC addition and higher the W/C, higher carbonation rates are resulted. Fig.10 suggests OPC content of around more than 30% is necessary for RC members with cover thickness of 40 to 75mm and with W/C=40% to 50% in order to sustain carbonation induced life time of 50 to 100 years.

Basic composition of the ECM cement at present is shown in Table 2 based on the above results and other research results on concretes and improved soils.

Table 2 –Basic Composition of ECM cement

Type	Finesse (cm^2/g)	Composition (%)		
		slag	OPC	others
For Concrete	6000	60~65	30~35	5~10
For Concrete	4000	62~67	28~33	5~10
For Soil	4000	62~67	26~31	5~12

PROPERTIES OF CONCRETE

Some examples of test results on fluidity, bleeding and setting time of the concrete using ECM cement (finess= 6000 cm^2/g) are shown in Fig.11. The fluidity of the concrete using ECM cement is slightly improved compared with that using ordinary Portland cement (OPC) or conventional type B blast-furnance slag cement (BB:slag content is 40 to 45%)). Bleeding is slightly decreased and initial setting time is delayed by 1 to 3 hours.

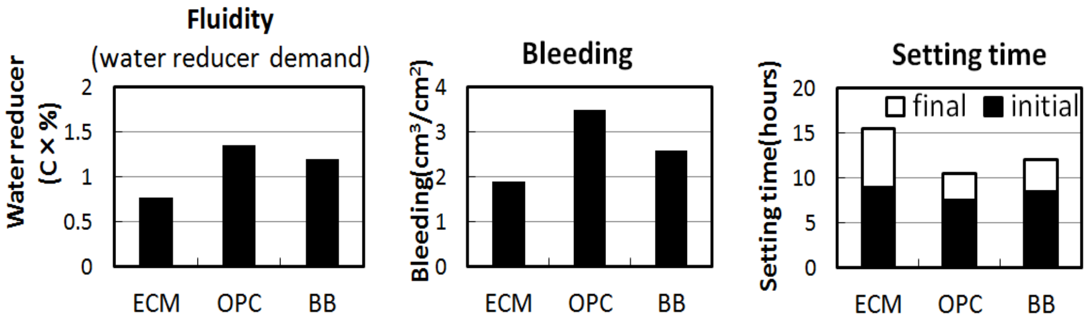


Figure 11 – Properties of fresh concrete (W/C=50%, slump=18cm, temperature=20℃)

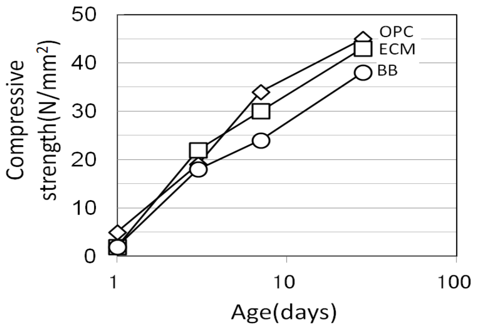


Figure 12 – Development of compressive strength of concretes (W/C=50%, slump=18cm, temperature=20℃)

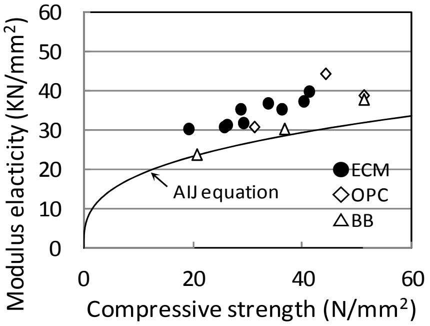


Figure 13 – Relations between compressive strength and modulus of elasticity of concretes

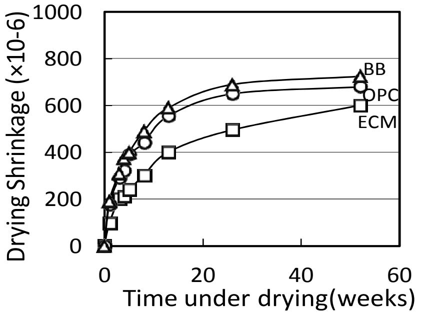


Figure 14 – Drying shrinkage of concretes (W/C=50%, slump=18cm, temperature=20℃, relative humidity=60%)

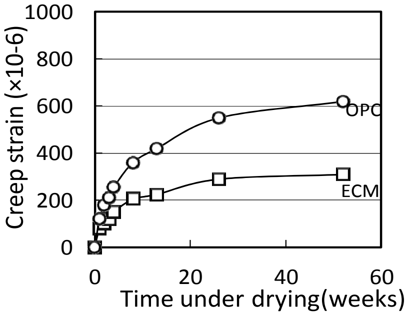


Figure 15 –Creep of concretes (W/C=50%, slump=18cm, temperature=20℃, relative humidity=60%, drying shrinkage is excluded)

Development of compressive strength with time is shown in Fig.12. The strength development in case of ECM cement is mostly the same as conventional cements (OPC, BB).

Fig.13 shows relations between modulus of elasticity and compressive strength; no difference is observed with concretes using different cements.

Fig.14 and Fig.15 show drying shrinkage and creep of concretes respectively. Both drying shrinkage and creep of concretes using ECM cement is decreased substantially. Slight reduction of drying shrinkage and creep of concretes by increasing slag content of blast-furnace slag cement is already reported (Yonekura 1986, Nakamoto 1996). The results shown in Fig.14 and Fig.15, however, are difficult to be explained by only increased slag content. The effects of high gypsum content will explain low drying shrinkage. Low creep may also be partly explained by high gypsum content, but it is still difficult to explain the results in Fig.14 in detail.

PROPERTIES OF IMPROVED SOIL

Results of compressive strength tests of improved clay soils from 4 different major city areas in Japan are shown in Fig.16. The strength is strongly influenced by the type of soil in both ECM cement and conventional type B blast-furnace slag cement (BB), but the strength of ECM cement is mostly higher than BB cement.

Fig.17 shows the results of dissolution test of 6-valent chromium Cr（Ⅵ） from improved 4 clay soils. The amount of Cr(Ⅵ) from ECM cement is much lower than BB cement; measured value is lower than measurable lower limit.

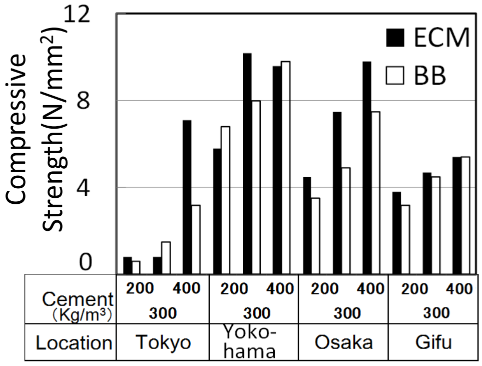


Figure 16 –Compressive strength of improved soil (cement slurry W/C=100%, temperature=20℃)

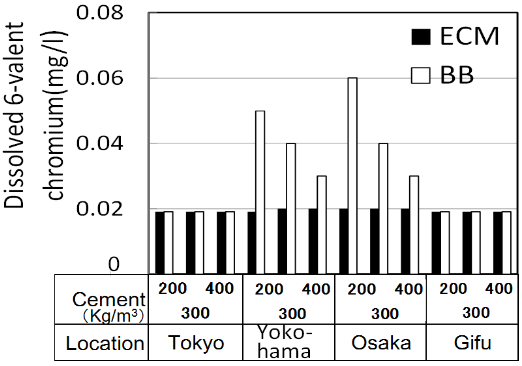


Figure 17 –Cr(Ⅵ)dissolution from improved soil (cement slurry W/C=100%, temperature=20℃)

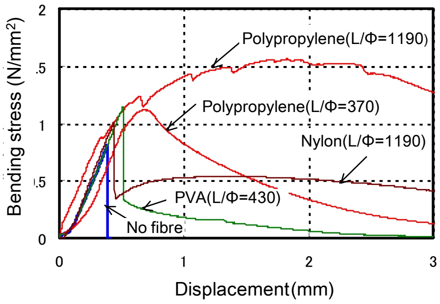


Figure 18 –Bending performance of fibre reinforced improved soils (cement content=200kg/m^3, cement slurry W/C=100%)

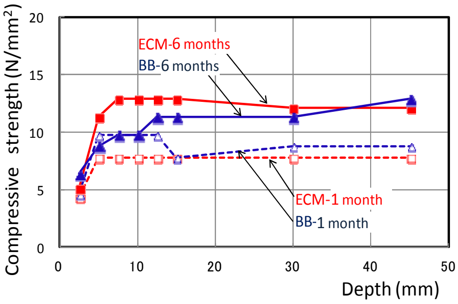


Figure 19 –Surface strength deterioration of improved soils in water (cement content=300kg/m^3, cement slurry W/C=60%)

Fig.18 shows relations between bending stress and displacement of organic fibre reinforced improved soil (40 × 40 × 160mm). The reinforcement obviously improves ductility of improved soil and the maximum effect is obtained in case of polypropelene fibre with length of 20mm and length diameter ratio of 1190.

Fig.19 shows results of durability tests of improved soils which were immersed in tap water. A strength decrease evaluated by needle penetration test is observed in the surface area up to the depth of around 5mm in both ECM cement and BB cement, but no difference is observed between them.

PERFORMANCES OF STRUCTURAL MEMBRES

Bonding performance of concrete to steel reinforcements is the most basic requirement for a new concrete using a new material such as ECM cement. The results of pull out bonding tests of concretes using ECM cement and ordinary Portland cement (OPC) showed no difference between the two concretes suggesting similar structural performances of the concrete using them (figures showing the results are abbreviated).

Fig.20 compares shear performances of the connecting zone of reinforced concrete (RC) beam-column members under cyclic load; the load is for evaluating performances of RC members against earthquake. No difference is observed between the concretes using ECM cement and OPC cement.

Fig.21 shows shear performances of a concrete filled tube column with steel reinforcement inside under cyclic loading. The performance, again, shows no difference between ECM cement and OPC cement. These results clearly demonstrate that ECM cement can be used for structural concrete members in the same manner as ordinary Portland cement.

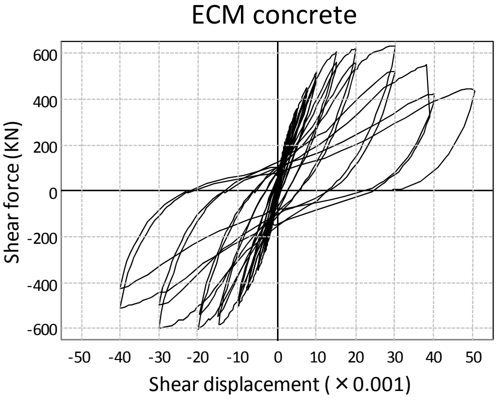


Figure 20 – Relation between sheer force and displacement of RC beam-column connection zone (concrete strength=38±2N/mm^2, shear reinforcement in connection zone=1.14%)

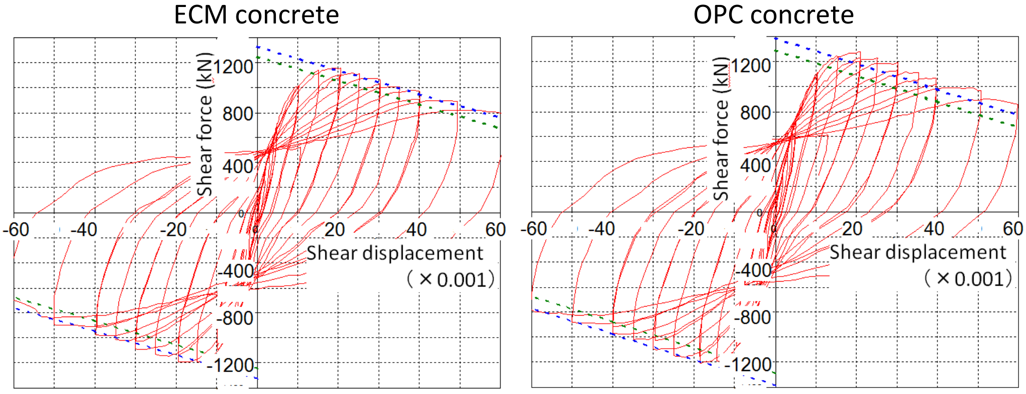


Figure 21 – Relation between sheer force and displacement of CFT column with steel reinforcement inside (concrete strength=72±3N/mm^2, diameter thickness ratio of steel =102, steel yield strength=451 N/mm^2, inside reinforcement=2.3%, reinforcement yield strength=705 N/mm^2)

ENERGY AND CO$_2$ REDUCTION BY ECM SYSTEM

When ECM system is utilized for structural members and improved soil, energy and CO$_2$ by cement production will be reduced in proportional to reduction of cement clinker content. The reduction is shown in Table 3 based on the composition of the ECM cement shown in Table 2.

The CO$_2$ foot print of a concrete is nearly the same as that of the cement used for the concrete since the contribution of aggregate is as low as around 5%. Reduction of CO$_2$ foot print of concrete by ECM cement is also shown in Table 3.

A trial design of eight floors flat was conducted to evaluate the effects of ECM cement on CO$_2$ foot print reduction of buildings. It is shown in Table 4 that the reduction is 40 to 50%

in case of above ground structures and around 30% in foundation. Thus introduction of ECM cement to building structures results in remarkable reduction of CO_2 foot print.

Table 3 CO_2 reduction of cement and concrete by ECM cement

Cement・Concrete	CO_2 reduction(%)	
	against OPC	against BB
ECM cement	60-70	30-45
ECM concrete	55-65	25-40

Table 4 CO_2 reduction of structures by ECM cement (a eight floors flat)

	Above ground		Foundation	
	RC	CFT	Improved soil	RC Pile
CO_2 reduction(%)	50-60	30-40	20-30	20-35

CONCLUSIONS

Separate efforts to reduce energy and CO_2 have been conducted in both cement industry and construction industry. ECM system, however, is a system to reduce them under corporation of cement and construction industries bringing their technologies together. The system is a combination of a newly developed high-slag cement and structures appropriate for it. It was shown that the combination achieves substantial reduction of energy and CO_2 of both cement and concrete structures sustaining sufficient qualities required for structures such as buildings.

The fundamental phase of the research and development work of the system has already finished and now the phase is at practical application study; usage of the system will start in due short time.

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