Third International Conference on Sustainable Construction Materials and Technologies http://www.claisse.info/Proceedings.htm

Properties of Extremely Dry Concrete made with Eco-cement and Recycled Coarse Aggregate

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ABSTRACT

We basically investigate such the mechanical properties as compressive and bending strengths, elastic modulus, and drying shrinkage of extremely dry concretes made by eco-cement and recycled coarse aggregate. The amount of carbon dioxide, CO_2, emission and utilization of industrial or general waste or by-products are estimated as environmental properties of the concrete. As a result, sufficient strengths are obtained even if recycled coarse aggregate is used. The drying shrinkage is clearly improved by the extremely dry concrete mixture. Therefore, the extremely dry concrete for Roller Compacted Concrete Pavement, RCCP, is quite suitable to use the both environment considering materials from the point of mechanical properties and environmental aspects.

Keywords. Eco-cement, Recycled coarse aggregate, Extremely dry concrete, Mechanical properties, Drying shrinkage

INTRODUCTION

The use of eco-cement or recycled aggregates is recommended from the standpoint of conservation of natural resources or sustainable development of the human society.
Eco-cement is produced with incinerated city waste ash as a main raw material. The cement contains more than 500 kg of the ash in 1000 kg of the cement. The quality of the cement is specified in Japanese Industrial Standard, JIS R 5214 (Japanese Standards Assoc., 2009). Since the ash contains relatively higher amount of alkali metals and chloride ion, the eco-cement also contains relatively higher amount of them. Therefore, it is necessary to decrease cement paste volume or cement content in the new concrete for a durable concrete structure.
The concrete containing recycled aggregates often shows higher volumetric change under drying condition. Because recycled aggregate particles are highly porous and having lower elastic modulus. The dimensional stability of recycled aggregate-concrete is improved by

applying the less volume of cement paste and dense cement paste structure.
The extremely dry concrete for roller compacted concrete pavement, RCCP, is suitable to use of the both eco-cement and recycled aggregates, because the concrete usually consists of lower volume of dense cement paste.
In this paper, we basically investigate such the mechanical properties as compressive and bending strengths, elastic modulus, and drying shrinkage of extremely dry concretes containing eco-cement and recycled coarse aggregate (Kimura et al., 2011). The amount of carbon dioxide, CO_2, emission and utilization of wastes or by-products are estimated as environmental properties of the environmental considering concrete.

EXPERIMENTAL PROCEDURE

Materials. An ordinary portland cement, C(N), and an eco-cement, C(E), are used as binder in the experiment. The density of the ordinary portland cement and the eco-cement are 3.16 g/cm^3 and 3.14 g/cm^3, respectively. Table 1 shows the properties of aggregates. The types of coarse aggregates are a crushed rock coarse aggregate, G(N), and type L recycled coarse aggregate, G(R), specified in JIS A 5023 appendix. Although the type L recycled coarse aggregate is not for structural use in the standard, if the results of the investigation show sufficient performance for type L recycled coarse aggregate, type M recycled coarse aggregate, which is specified in JIS A 5022 appendix as structural use in particular situation, can be used safely to the RCCP. As shown in Table 1, the recycled coarse aggregate has higher water absorption of 6.39 %, it also has higher solid content of 61.6%. That is, the recycled coarse aggregate consists of relatively porous and rounded particles.
Table 2 summarizes the specifications on physical properties for three types of recycled coarse aggregates in Japanese Industrial Standards.

Table 1. Physical properties of aggregates

type	symbol	density (g/cm^3)		absorption (%)	unit weight (kg/L)	solid content (%)	F.M.
		s.s.d.	oven-dry				
crushed sand	S	2.63	2.59	1.45	1.71	66.0	2.82
crushed rock coarse agg.	G(N)	2.68	2.65	1.00	1.54	57.9	6.81
recycled coarse agg. type L	G(R)	2.38	2.24	6.39	1.38	61.6	6.83

Table 2. Physical properties for recycled coarse aggregates specified in JIS

type	oven-dry density (g/cm^3)	absorption (%)	abrasion loss (%)	finer particle content (%)	JIS
H	>2.5	<3.0	<35	<1.0	JIS A 5021
M	>2.3	<5.0	-	<1.5	JIS A 5022 appendix.
L	-	<7.0	-	<2.0	JIS A 5023 appendix.

Mixture proportions of concrete. Table 3 shows mixture proportions of extremely dry concretes. The "Ex" stands for extremely dry concrete. Next "N" and "E" show ordinary portland cement and eco-cement, respectively. In addition the next "N" and "R" indicate coarse aggregate types, the "N" and "R" mean crushed rock coarse aggregate and recycled coarse aggregate, respectively. The last numerics show the water cement ratios of 30, 35 and 40 %. The water cement ratio varies under the condition of the ratio of mortar volume to inter particle space of coarse aggregate, "Km", of 1.6 and unit water content of 125 kg. The "Kp" means the ratio of cement paste volume to inter particle space of fine aggregate.
Table 4 shows mixture proportion of traditional plastic concrete for pavement. It has

slumping consistency of 3 cm. The water cement ratio of the concrete is 50%, and unit bulk volume of coarse aggregate is 0.73 m^3. The traditional concrete is made by ordinary portland cement and crushed rock coarse aggregate.

Table 3. Mixture proportions of extremely dry concretes

symbol	w/c (%)	Km	Kp	unit content (kg/m^3)					
				W	C(N)	C(E)	S	G(N)	G(R)
Ex-NN30	30		1.78		417		735		-
Ex-NN35	35	1.6	1.55	125	357		784	1243	-
Ex-NN40	40		1.39		313		821		-
Ex-EN30	30		1.8		-	417	732		-
Ex-EN35	35	1.6	1.56	125	-	357	782	1243	-
Ex-EN40	40		1.4		-	313	820		-
Ex-ER30	30		2.08		-	417	632	-	
Ex-ER35	35	1.6	1.78	125	-	357	682	-	1194
Ex-ER40	40		1.59		-	313	720	-	

Table 4. Mixture proportion of traditional pavement concrete

symbol	w/c (%)	slump (cm)	air (%)	unit bulk volume of coarse agg. (m^3)	sand percent s/a	unit content (kg/m^3)				
						W	C(N)	S	G(N)	WR (C*%)
PN	50	3.0	5.0	0.73	0.39	160	320	699	1133	0.4

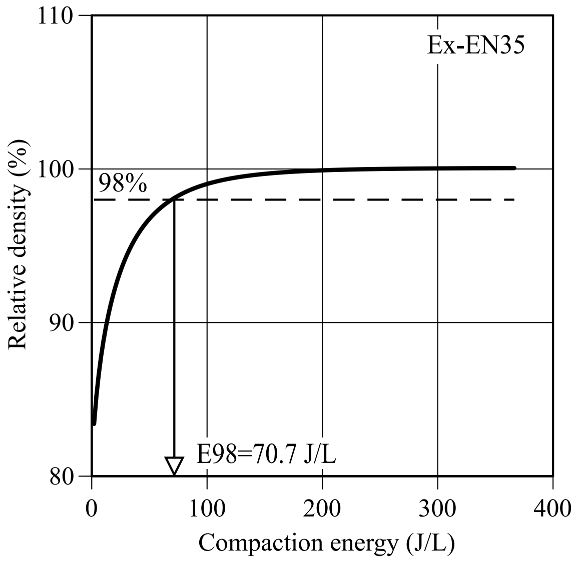

Figure 1. An example of consolidation curve (Ex-EN35)

Compaction property. The ease or difficulty of compaction for the extremely dry concretes is quantified by "compactability test" according to JSCE-F 508 (Japan Society of Civil Engineers, 2007). The freshly mixed extremely dry concrete is set on vibration table. Then it is compacted with specified acceleration of 49 m/s^2 (5G) and frequency of 75 Hz for 3 minutes. The consolidation curve is resulted from the test. An example of the results is shown in Figure 1. The curve shows the relationship between compacting energy and relative density of the specimen. The energy is calculated by the mass of the concrete, acceleration, frequency and duration of vibrating as shown in equation (1). The ease of the compaction is expressed by "E98" which means the energy for 98% relative density of the concrete. That is, the lower E98 shows higher compactability of the concrete.

$$E=m*\alpha_{max}^2*t / 4\pi^2 f \quad (1)$$

where; E=compaction energy (J/L), m=density of sample concrete (kg/L), α_{max}=max. acceleration (m/s^2), t=vibrating time (s), f=frequency (1/s)

Compressive strength and elastic modulus. The compressive strength and elastic modulus of concrete are examined according to corresponding JIS. The cylinder specimens having 100 mm diameter and 200 mm height after the compactability test are used for the tests. Therefore, relative density of each specimen is obtained before the tests. This can calculate cement void ratio of each specimen. The specimens are cured in 20 degrees C. water for 28 days.

Bending strength. The bending strength of concrete is tested according to JIS A 1106. The specimens for the test have 100 x 100 mm cross section and 400 mm length. The bending span is 300 mm. The specimens are bent by two concentrated loads with 100 mm distance. They are cured in 20 degrees C. water for 28 days.

Drying shrinkage. The drying shrinkage and change in mass of the extremely concrete made with the w/c of 35% and traditional plastic concrete are measured based on JIS A 1129-2, which specifies test method for length change by contact gauge. The specimens have the 100 x 100 x 400 mm geometry and the base length is 200 mm. They are cured in 20 degrees C. water for 7 days and measured the initial length and mass. Then the specimens are stored under the constant condition of 20 degrees C. and 60% R.H. for 6 months.

Estimation of CO_2 emission and utilized waste of concretes. Table 5 shows CO_2 emission from each concrete making material to estimate the CO_2 emission from each extremely dry concrete mixture. The 766.6 kg-CO_2/ton for ordinary portland cement and 784.0 kg-CO_2/ton for eco-cement are used for the estimation (Japan Society of Civil Engineers, 2004). Also the 3.1 kg-CO_2/ton and 2.9 kg-CO_2/ton are used for the recycled coarse aggregate and crushed rock coarse aggregate, respectively. The estimation in here does not include such the other commonly used materials as mixing water and fine aggregate. Table 5 also gives the utilized wastes mass in the ordinary portland cement and the eco-cement as raw materials. It does not include utilized waste mass as energy source. That for the ordinary portland cement of 248 kg-waste/ton is calculated from the public data in summaries of LCI data for cement (Japan Cement Assoc., 2012). That for the eco-cement of

Table 5. CO_2 emission and utilized waste mass of materials

material	CO_2-emission (kg-CO_2/ton)	utilized waste (kg-waste/ton)
ordinary portland cement	766.6	248
eco-cement	784.0	680
crushed rock coarse agg.	2.9	0
recycled coarse agg.	3.1	1000

680 kg-waste/ton is also calculated with the public data from Tokyo Tama Eco-cement (Tama Junkankumiai, 2012). All the recycled coarse aggregate content is directly treated as the utilized waste.

RESULTS AND DISCUSSIONS

Compactability. Figure 2 shows the relationship between w/c and E98 of each extremely dry concrete. The water cement ratio does not influence directly on compactability of the extremely dry concrete, since the compaction of extremely dry concrete is significantly affected by constitution of solid particles, especially coarser particles. The mixtures made with the eco-cement, Ex-EN, have lower E98 than the ordinary portland cement mixtures, Ex-NN. Although a little lower density of eco-cement relates to a little higher volume of cement paste for eco-cement mixtures, the both series mixtures have almost the same volumetric constitution in the mixture. Therefore the lower E98 for eco-cement mixtures might be resulted from physical or chemical properties of the eco-cement.
The E98 of the mixtures containing recycled coarse aggregate, Ex-ER, are clearly lower than crushed coarse aggregate mixtures, Ex-EN. The relatively rounded particle shape might cause these results.

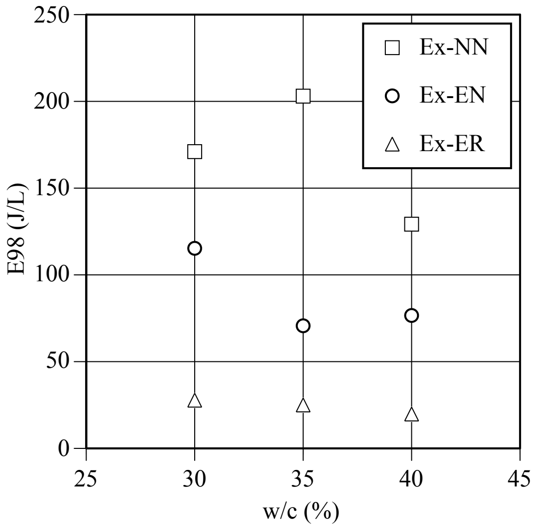

Figure 2. E98 of extremely dry concretes

Compressive strength and elastic modulus. Figure 3 shows the relationship between cement void ratio and compressive strength of extremely dry concretes. The eco-cement and crushed rock coarse aggregate mixture, Ex-EN, exhibits almost 0.9 times of compressive strength compared with the ordinary portland cement mixture, Ex-NN. If the recycled coarse aggregate is used, Ex-ER, the compressive strength decreases almost 0.8 times of that of the crushed rock coarse aggregate mixture, Ex-EN, at the same cement void ratio. However, it is higher than 50 N/mm^2 even the lowest compressive strength. Therefore, the extremely dry concretes in our investigation have sufficient strength for pavement. In addition, the cement void ratio directly relates to the compressive strength of each extremely dry concrete. These results shows that the compressive strength is controlled by the ratio.
Figure 4 shows relationship between compressive strength and elastic modulus of extremely dry concretes. The eco-cement extremely dry concrete, Ex-EN, has a higher elastic modulus

at the same compressive strength than ordinary portland cement mixture, Ex-NN, which contains same coarse aggregate in equal content in the mixture. Even the mixture using eco-cement and recycled coarse aggregate, Ex-ER, has sufficient elastic modulus for pavement concrete. It is more than 32 kN/mm^2. The elastic modulus can be estimated with compressive strength according to traditional relationship proposed in Standard Specifications for Reinforced Concrete by Japan Society of Civil Engineers.

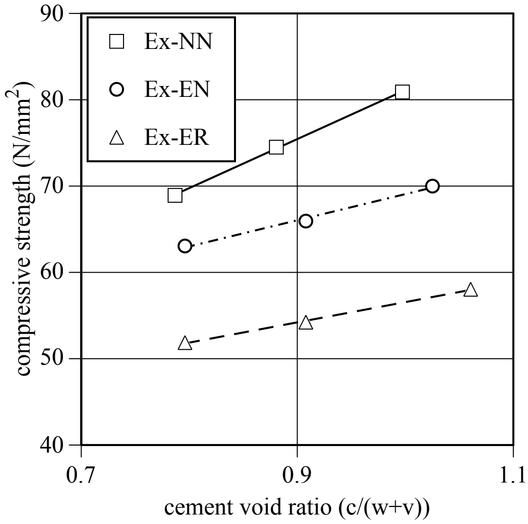

Figure 3. Cement void ratio and compressive strength

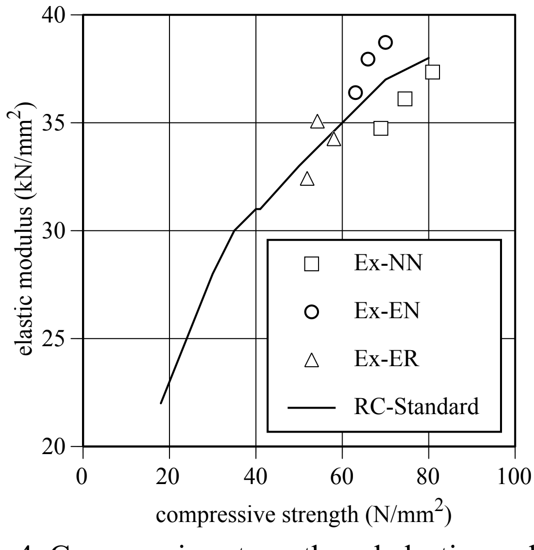

Figure 4. Compressive strength and elastic modulus

Bending strength. The relationship between compressive strength and bending strength of the extremely dry concrete is shown in Figure 5. Bending strength of eco-cement mixtres are higher than that of ordinary portland cement mixtures at the same compressive strength. Although Ex-ER40 mixture has lowest bending strength in the experiment, it is grater than 6.5 N/mm^2. Since the specification for pavement in Japan often requires higher than 4.5 N/mm^2

bending strength, the eco-cement extremely dry concretes in the experiment have sufficient bending strength even if the recycled coarse aggregate is used for the mixture. The bending strength of the extremely dry concretes made by the eco-cement or eco-cement and recycled coarse aggregate can be obtained according to corresponding compressive strength in the same way of ordinary portland cement concrete.

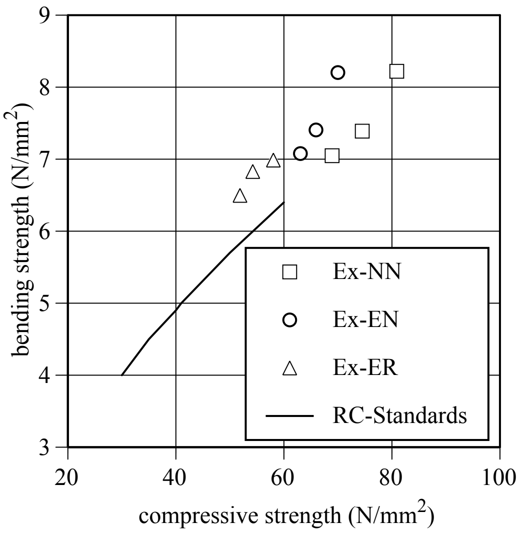

Figure 5. Compressive and bending strength

Drying shrinkage. Figure 6 and Figure 7 show the mass decreasing and length change of extremely dry concretes and traditional pavement concrete under drying condition, respectively. Mass decreasing and drying shrinkage of the extremely dry concrete with eco-cement and crushed rock coarse aggregate, Ex-EN35, are similar to the ordinary portland cement mixture, Ex-NN35. Although the extremely dry concrete with eco-cement and recycled coarse aggregate, Ex-ER35, exhibits higher mass decreasing than other two extremely dry concretes, the drying shrinkage of the mixture does not clearly increase. The difference of drying shrinkage between the recycled coarse aggregate mixture and the crushed rock coarse aggregate mixture is limited to lower than 100×10^{-6}. This result suggests that extremely dry concrete is quite suitable for the concrete containing relatively lower density or highly porous coarse aggregate.

Drying shrinkage of extremely dry concretes significantly decreases compared with traditional pavement concrete, PN. Since the lower drying shrinkage of concrete relates to longer interval of joints on the pavement, the extremely dry concrete is appropriate for eco-cement and recycled coarse aggregate.

Environmental aspects. Assuming that the CO_2 is emitted from only the cement and coarse aggregate, the estimated CO_2 emission from each concrete in our investigation is shown in Table 6 and Figure 8. Table 6 and Figure 8 also give utilized waste content as raw material for ordinary portland cement and eco-cement. In the case that if the recycled coarse aggregate is used for the mix, all the recycled coarse aggregate mass is added to the utilized waste content in eco-cement. Lower water cement ratio causes higher CO_2 emission by higher cement content. The eco-cement mixtures with crushed rock coarse aggregate, Ex-EN, show slightly higher CO_2 emission than the case of the ordinary portland cement mixtures,

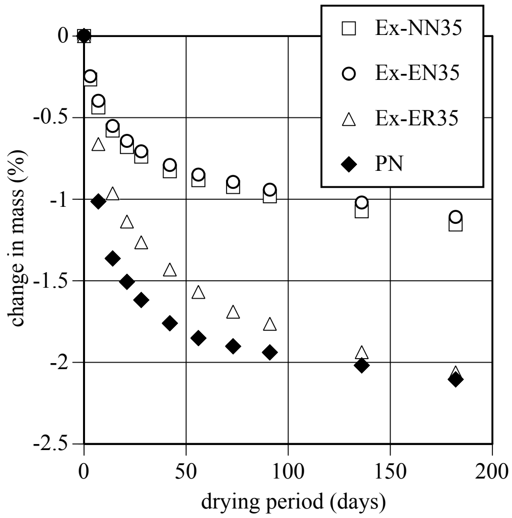

Figure 6. Mass decreasing of concretes

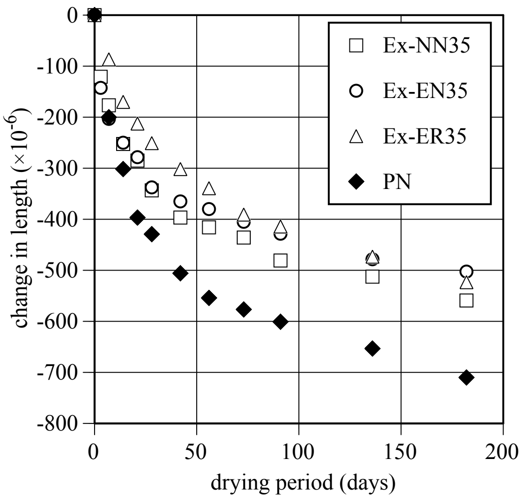

Figure 7. Drying shrinkage of concretes

Table 6. CO_2 emission and utilized waste mass for each extremely dry concrete

symbol	CO_2-emission ($kg\text{-}CO_2/m^3$)	utilized waste ($kg\text{-}waste/m^3$)
Ex-NN30	323.3	103.4
Ex-NN35	277.3	88.5
Ex-NN40	243.6	77.6
Ex-EN30	330.5	283.6
Ex-EN35	283.5	242.8
Ex-EN40	249.0	212.8
Ex-ER30	330.6	1477.6
Ex-ER35	283.6	1436.8
Ex-ER40	249.1	1406.8

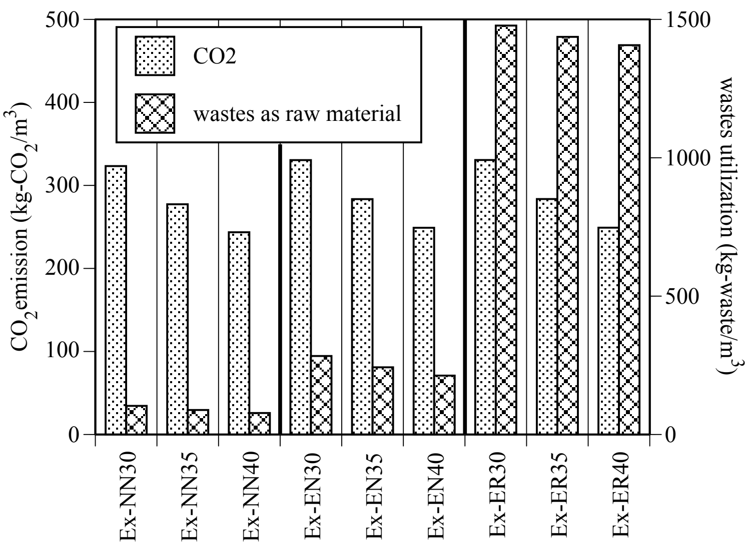

Figure 8. CO_2 emission and utilized waste mass for each extremely dry concrete

Ex-NN. However, the utilized waste mass increases for the case of eco-cement concrete mixtures, Ex-EN, compared with the ordinary portland cement mixtures, Ex-NN. It sharply increases for the case of recycled coarse aggregate mixtures, Ex-ER. The decision of the priority of environmental influencing factors, for example CO_2 emission and waste utilization etc., might be a significant matter on environmental consideration.

CONCLUSIONS

In the study, we investigate basic mechanical or dimensional properties, compressive and bending strength, elastic modulus, drying shrinkage of extremely dry concrete with eco-cement and recycled coarse aggregate. The CO_2 emission and utilized waste mass in the concretes are also investigated. The conclusions of the investigation are as follows:
(1) Eco-cement extremely dry concrete has higher compactability than ordinary portland cement extremely dry concrete.
(2) Eco-cement extremely dry concrete has sufficient compressive and bending strength and elastic modulus for pavement use.
(3) Elastic modulus and bending strength can be calculated based on the compressive strength.
(3) Drying shrinkage of extremely dry concrete is clearly improved by less unit water content and cement paste volume, even if it contains highly porous coarse aggregate.
(4) Eco-cement extremely dry concrete and eco-cement recycled coarse aggregate extremely dry concrete emit slightly higher amount of CO_2 than ordinary portland cement extremely dry concrete. However, the utilized waste mass in the concrete increases with the use of the eco-cement and recycled coarse aggregate.

ACKNOWLEDGEMENT

This investigation is carried out as joint research with Taiheiyo Cement Corp. Also the authors would like to appreciate to Mr. Jyunya KIMURA with experimental help in his master's course at Graduate school of Tokyo Metropolitan University.

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