- Technical Paper -

EFFECT OF BINDER AND AGGREGATE TYPE ON MECHANICAL AND ENVIRONMENTAL PERFORMANCE OF GREEN CONCRETE

German PARDO[*1], Michael HENRY[*2], Tsugio NISHIMURA[*3] and Yoshitaka KATO[*4]

ABSTRACT
In this paper the effect of binder composition and volume and aggregate type on mechanical and environmental performance of green concrete using fly ash and recycled aggregate in order to reduce CO_2 emissions and consumption of raw materials respectively were evaluated. From the results obtained it was found that concrete containing high volume of recycled materials is a good option due to its good mechanical and environmental performance as compared with normal concrete.
Keywords: green concrete, environmental impact, fly ash, recycled aggregate.

1. INTRODUCTION

It is well known the increasing necessity of taking care of our planet in order to preserve it for the future generations which has been commonly understood as sustainable development. On this regard the concrete industry can play an important role. Carbon dioxide (CO_2) is the primary greenhouse gas contributing to climate change, and some researchers estimate that the manufacture of Portland cement is responsible for roughly 7% of the world's total emissions [1]. The consumption of natural resources like aggregate, water, and sand is another important item, due to the limited resources.

In order to reduce the carbon dioxide emissions and preserve raw materials, we are developing concrete which replaces cement with fly ash, and normal aggregate with recycled aggregate. The use of fly ash, a by-product of the coal industry, has been investigated extensively in concrete, and high-volume fly ash concrete has been shown to have excellent durability as well as reduced environmental impact and cost [1]. Concrete production requires large amounts of natural resources such as sand and gravel, but this consumption can be reduced by recycling demolition waste into aggregates. Concrete with total replacement of normal coarse aggregates with recycled aggregates has been investigated and satisfactory concrete quality was reported [2]. However, most of the previous works on this regard focused on replacing a single concrete component or some combination in few amounts [3]; therefore one of our main objectives is combining fly ash and recycled aggregates in high percentage.

For this purpose different concrete mixes were designed in order to evaluate the low and normal binder ratio, aggregate type and fly ash effect. To obtain a good mechanical performance a low water binder ratio was set in advance, knowing that including recycled aggregates has a reduction effect on concrete strength. All results obtained were compared with a concrete series set as reference having common mix proportions for concrete used in common constructions in Japan. Finally the balance between the mechanical and environmental performance was evaluated using the environmental performance indicator, which normalizes the mechanical performance by environmental impact.

2. EXPERIMENTAL WORK

2.1 Materials

Concrete was prepared using water (W), type 1 Portland cement (C), river sand (S), normal aggregates (NA), JIS grade L recycled aggregates (RA), JIS type II fly ash (FA), and air entraining (AE) and super plasticizer (SP) admixtures. Properties of recycled aggregate and fly ash are given in Table 1.

Table 1 Recycled aggregate and fly ash properties

Physical properties	Value
Recycled aggregate	
Density (kg/m^3)	2430
Absorption capacity (%)	5.81
F.M.(%)	6.73
Fly ash	
Density (kg/m^3)	2290
Blaine fineness (m^2/kg)	408.7
Ignition loss (%)	2.2

2.2 Mix proportions

Mix proportions are given in Table 2. The term binder (B) is used to represent all cementitious materials – in this case, fly ash and Portland cement. All mixes used a constant water-binder ratio of 0.3 and

*1 Master student, Department of Civil Engineering, The University of Tokyo, JCI Member
*2 Doctoral student, Department of Civil Engineering, The University of Tokyo, JCI Member
*3 Senior technical support specialist, Institute of Industrial Science, The University of Tokyo, JCI Member
*4 Associate professor, Institute of Industrial Science, The University of Tokyo, JCI Member

Table 2 Mix proportions

<table>
<tr><th rowspan="2">Series</th><th colspan="3">Material ratios</th><th colspan="6">Mix proportions
(kg/m^3)</th></tr>
<tr><th>W/B</th><th>FA/B</th><th>s/a</th><th>W</th><th>C</th><th>FA</th><th>S</th><th>NA</th><th>RA</th></tr>
<tr><td>Control</td><td>0.5</td><td>-</td><td>0.43</td><td>171</td><td>342</td><td>-</td><td>746</td><td>1015</td><td>0</td></tr>
<tr><td>NB-NA</td><td rowspan="8">0.3</td><td rowspan="4">-</td><td rowspan="8">0.39</td><td rowspan="2">165</td><td rowspan="2">550</td><td rowspan="4">-</td><td rowspan="2">624</td><td>1009</td><td>-</td></tr>
<tr><td>NB-RA</td><td>-</td><td>905</td></tr>
<tr><td>LB-NA</td><td rowspan="2">135</td><td rowspan="2">450</td><td rowspan="2">687</td><td>1111</td><td>-</td></tr>
<tr><td>LB-RA</td><td>-</td><td>996</td></tr>
<tr><td>NB-NA-FA50</td><td rowspan="4">0.5</td><td rowspan="2">165</td><td rowspan="2">275</td><td rowspan="2">275</td><td rowspan="2">590</td><td>955</td><td>-</td></tr>
<tr><td>NB-RA-FA50</td><td>-</td><td>856</td></tr>
<tr><td>LB-NA-FA50</td><td rowspan="2">135</td><td rowspan="2">225</td><td rowspan="2">255</td><td rowspan="2">659</td><td>1067</td><td>-</td></tr>
<tr><td>LB-RA-FA50</td><td>-</td><td>957</td></tr>
</table>

sand-aggregate ratio of 0.39, except by control series (reference series) which water-binder ratio was 0.5 and sand-aggregate ratio was 0.43. The effect of binder volume was obtained by varying the amount of binder from 550 kg/m^3 (normal binder) to 450 kg/m^3 (low binder), and at both binder volumes two compositions were used: 100% cement or 50% cement-50% fly ash. Both normal and recycled aggregates were used for all combinations of binder volume and composition to test the effect of aggregate type.

2.3 Fresh concrete properties

Fresh concrete properties are given in Table 3. Slump and air content were measured according to JIS A 1101-1998 and JIS A 1128-2005, respectively. The slump and air content target were 10-12cms and 5% respectively, however for some of the series it was not possible, nonetheless the concrete had good workability.

2.4 Specimens & curing

Cylinder (10Ø×20cm) and beam (10×10×40cm) specimens were cast for each concrete mix following JSCE-F 552-1999. After casting, molded specimens were covered in plastic wrap and cured in the molds until they were hard enough: 24 hours (non-fly ash concrete) or 48 hours (fly ash concrete), after which they were removed from the molds and water cured up to 28, 56 or 91 days.

2.5 Mechanical performance evaluation

Two mechanical properties of the concrete mixes were tested experimentally. Compressive strength was measured according to JIS A 1108-2006 and tested at 7, 28, 56, and 91 days; flexural strength was measured according to JSCE-G 552-1999 and tested at 28 and 91 days. For all tests, the reported values are the average of three specimens.

2.6 Environmental impact evaluation and environmental performance indicator

Environmental impact was evaluated using the CO_2 footprint and volume of raw materials. The CO_2 footprint was calculated from the mix proportions given in Table 1 and the CO_2 inventory data for concrete-making materials given in Table 4. The volume of raw materials was calculated by the percent volume of cement, water, sand, and normal aggregates per cubic meter of concrete as a simple summation.

The environmental performance indicator (EPI) is an assessment factor which considers both the mechanical and environmental performances [5]. In this research, the EPI was calculated as the ratio of the mechanical performance (compressive strength at 91 days) to the environmental impact (CO_2 footprint and volume raw materials).

3. MECHANICAL PERFORMANCE RESULTS

3.1 Compressive strength

Compressive strength results are shown in Fig. 1 for 7, 28, 56, and 91 days curing. It can be seen that all non-fly ash concrete series have higher compressive strength than control series, whereas just fly ash concrete with normal aggregate achieves higher strength than control mix after 28 days. Among non-fly ash, concrete without recycled aggregate shows a strength development in time in a rate similar than control concrete, however concrete with recycled aggregate does not show any strength gain from 28 to 91 days, this results may indicate that the strength of the matrix reached or exceeded the strength of recycled aggregate, therefore the strength of the concrete is limited by the strength of the recycled aggregate.

Table 3 Fresh concrete properties

Series	Slump (mm)	Air content (%)
Control	11.0	4.0
NB-NA	18.5	5.1
NB-RA	12.0	5.2
LB-NA	8.5	3.5
LB-RA	7.5	4.5
NB-NA-FA50	10.0	3.0
NB-RA-FA50	16.0	4.5
LB-NA-FA50	15.0	2.0
LB-RA-FA50	16.0	4.0

Table 4 CO_2 emission values [4]

Material	CO_2 emissions ($kgCO_2$/ton)
Portland Cement	766.5
Fly ash	19.6
Natural river sand	3.7
Normal aggregates	2.9
Recycled aggregates	3.1

For fly ash series the strength development in time after 7 days is faster than their counterpart non-fly ash series due to the delayed but steady reaction of fly ash compared with cement, being marked from 7 to 28 days, overtaking the control series the fly ash with normal aggregate concrete, that also shows a strength development a greater rate than control; however fly ash concrete with recycled aggregate has a strength development at similar rate than control after 28 days.

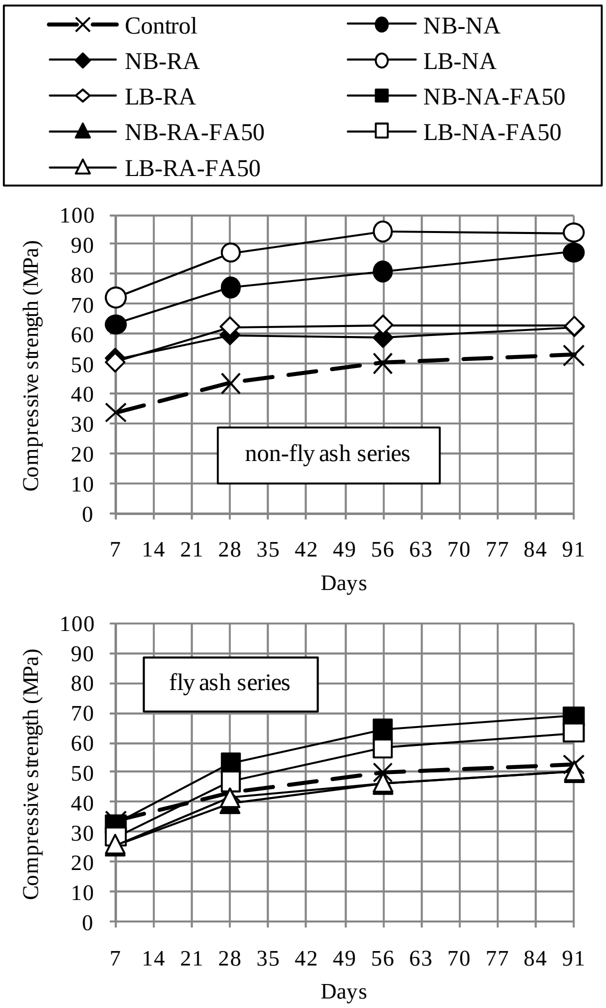

Figure 1 Compressive strength development

In all cases, the recycled aggregate series are weaker than their counterpart normal aggregate series, but the difference is more pronounced for non-fly ash than for fly ash concrete because the strength of the non-fly ash mortar matrix is higher. The weakness of recycled aggregates may be due to the waste material coating the aggregate, which could reduce the bond between the aggregate and the cement matrix, and some cases of aggregate coming off were observed as shown in Fig. 2. Similarly, all the fly ash series are weaker than their counterpart non-fly ash series, but the difference is greater for normal aggregates.

When normalizing the results with control series as shown in Fig. 3 it can be seen that non-fly ash concrete tends to reduce the difference in strength with control series, this is due to the early strength development of concrete with low water-cement ratio. Conversely fly ash concrete shows a better performance in time than control series, proving the slowly but steady strength development of fly ash. It can be seen also from the figures that for non-fly ash concrete, the series with low binder do not show strength development between 56 and 91 days. Finally, for normal aggregate non-fly ash concrete, the low binder specimens are stronger than the normal binder specimens; this may be due to the greater amount of aggregate, which increases the strength of the mix. In contrast, for normal aggregate fly ash concrete, the normal binder specimens are slightly stronger than the low binder specimens. For both binder compositions, there is almost no difference in strength between recycled aggregate concretes.

Fig. 2 Failure plane of recycled aggregate concrete

3.2 Flexural strength

Flexural strength results are shown in Fig. 4 for 28 and 91 days curing. Flexural strength for non-fly ash normal aggregate concrete are higher and shows greater rate than control one, and non-fly ash recycled aggregate concrete does not show development strength in time, even low binder mix has an unusual and unexplained decrease in strength and normal binder series has slightly lower flexural strength than control mix. The difference between normal and recycled aggregate concrete is marked, and the low binder concrete also shows higher strength than normal binder, but the difference for 91 days is lower than 28 days.

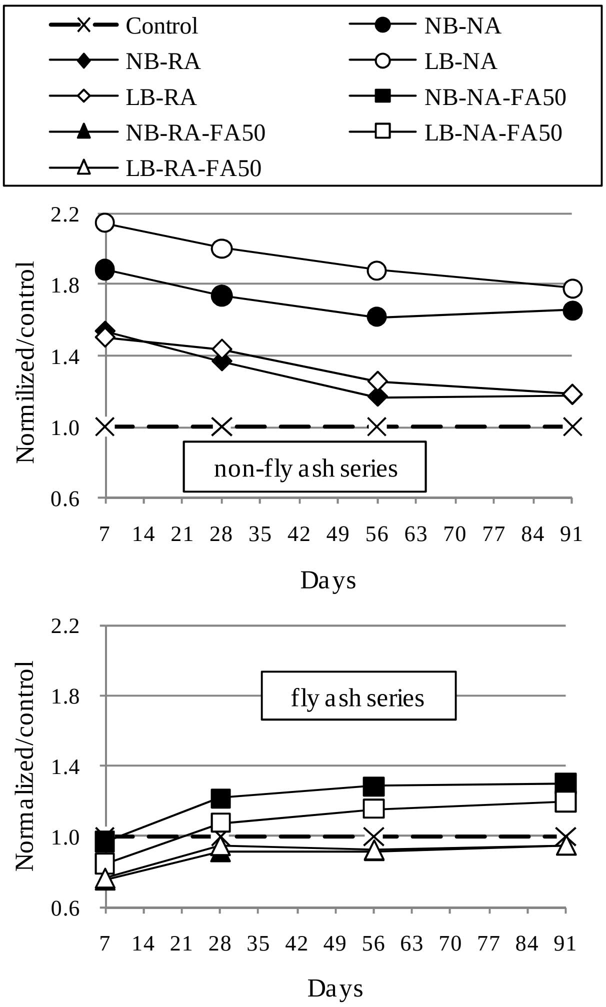

Fig. 3 Compressive strength development normalized by control series

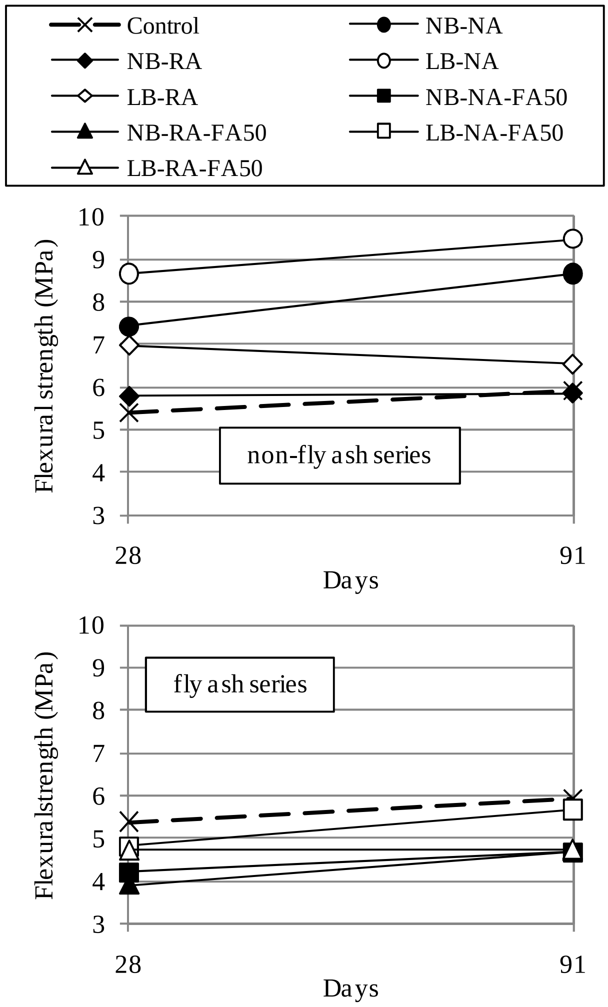

Fig. 4 Flexural strength development

The concrete with fly ash all series have lower flexural strength than control series. At 28 days the low binder concrete has higher flexural strength than normal binder, the same happens for concrete with normal and recycled aggregate respectively, however the difference is not so big. And at 91 days normal binder concrete and low binder recycled aggregate concrete have almost same flexural strength, but low binder normal aggregate concrete still has higher strength. All series show a slightly greater strength development in time than control series, except for the low binder recycled aggregate series that does not show any strength development.

Low binder recycled aggregate series don not show any increase in strength which may be caused for the loss in bonder strength between recycled aggregate and mortar paste due to some dust coating the recycled aggregate. This is not observed in normal binder series since they have more cement content which tackles in somehow the problem.

In general, the recycled aggregate series are weaker than their counterpart normal aggregate series, but the difference is more pronounced for non-fly ash than for fly ash because the weakness of the fly ash mortar matrix, whereas the non-fly ash matrix is strong enough that the aggregate shape has some influence in the failure plane. Similarly, all the fly ash series are weaker than their counterpart non-fly ash series, but the difference is greater for normal aggregates.

4. ENVIRONMENTAL PERFORMANCE

4.1 Environmental impact

The CO_2 emissions per series are shown in Fig. 5. The non-fly ash concrete has higher CO_2 emissions than normal concrete, this is due to the large amount of cement which is the principal contributor among the concrete materials, and the low binder mixes also have lower emissions than normal binder. For fly ash series, all series have less CO_2 emissions than control series, this is due to the large amount of cement substituted with fly ash, and also the low binder mixes have lower emissions than normal binder. There is no difference between normal and recycled aggregate series since both have the same CO_2 footprint.

The volume of raw materials is shown in Fig. 6. Since the recycled materials used were fly ash and recycled aggregate, just those series have an effect on raw material preserved.

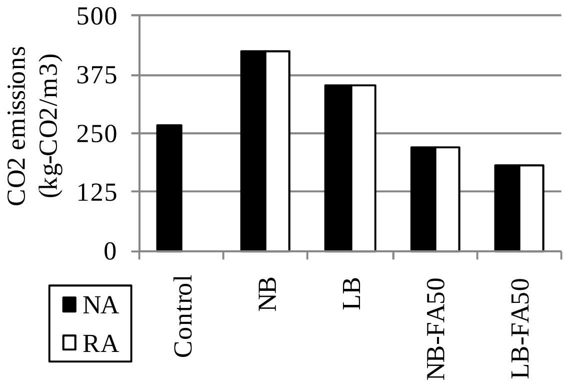

Fig. 5 CO_2 emissions per series

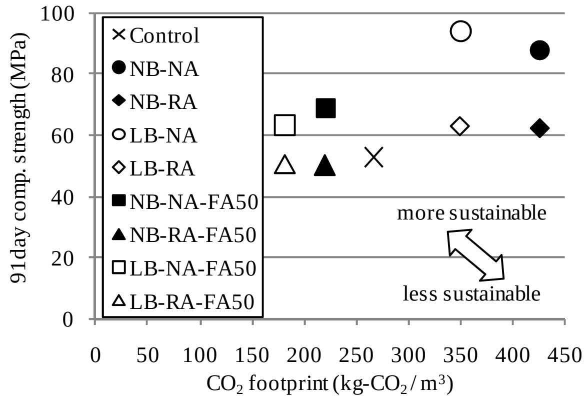

Fig. 7 Compressive strength vs. CO_2 footprint

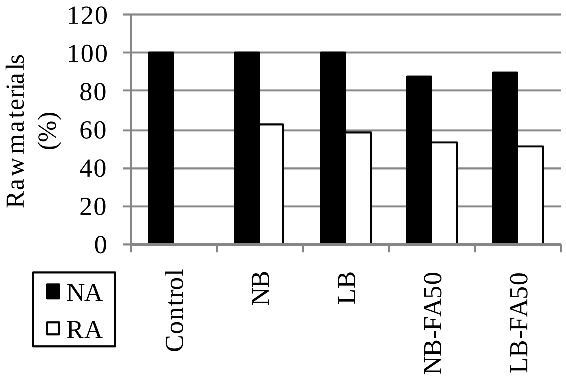

Fig. 6 Volume of raw materials per series

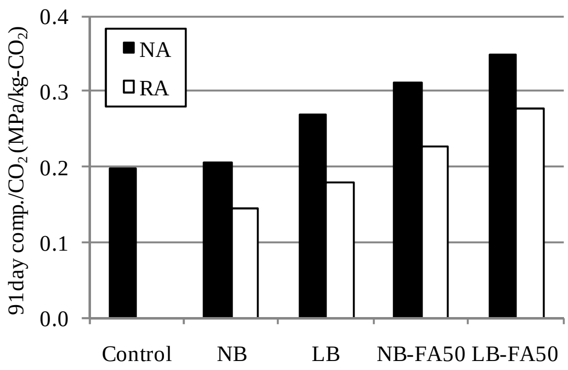

Fig. 8 EPI for compressive strength and CO_2

The series with fly ash and recycled aggregate have a volume of raw materials close to 50 percent of total volume. The series with just recycled aggregate have a volume of raw materials near to 60 percent of total volume, and series with just fly ash have a volume of raw materials around 90 percent of total volume. The biggest contributor is the normal aggregate; for series with recycled aggregate with and without fly ash, the volume of raw materials is a little bit lower for low binder than for normal binder series, but series with just fly ash, the effect is opposite.

4.2 Mechanical vs. environmental

(1) Compressive strength vs. CO_2 footprint

In Fig. 7 are shown the 91-day compressive results against CO_2 footprint and in Fig. 8 are the compressive strength-CO_2 EPI values. From Fig. 7 can be observed that there are two main groups: fly ash and non-fly ash concrete. The tendency is of increasing strength when increasing CO_2 footprint, however fly ash series with normal aggregate has more compressive strength than non-fly ash recycled aggregate series while having much less CO_2 footprint. Non-fly ash concrete with normal aggregate has more compressive strength than control one and fly ash concrete with recycled aggregate has lower but still similar compressive strength than control series. Being more sustainable the concrete with less CO_2 footprint while having good compressive strength compared with control series.

From Fig. 8 it can be seen that normal aggregate series have higher EPI than recycled aggregate series, and among this the series without fly ash has lower EPI than control one, this is due to a reduction in strength without a reduction in cement content. The series with highest EPI are fly ash series with normal aggregate. The EPI for low binder fly ash series with recycled aggregate is higher than non-fly ash series and fly ash normal binder recycled aggregate series. The EPI for low binder series is also higher than normal binder series.

(2) Compressive strength vs. volume of raw materials

In Fig. 9 are shown the 91-day compressive results against volume of raw materials and in Fig. 10 are the compressive strength-raw materials EPI values. From Fig. 9 can be said that the biggest difference exists between normal and recycled aggregate series, decreasing strength when utilizing recycled aggregate. And comparing fly ash and non-fly ash series exists also the same trend, however the difference is small as compared with aggregate type difference. Compared with control series, all other mixes have higher compressive strength except fly ash recycled aggregate series but the difference is so small; and equal or less consumption of raw materials. Being more sustainable the concrete with less consumption of raw materials while having good compressive strength compared with control series. From Fig. 10 can be observed that recycled aggregate series have higher EPI value than normal aggregate series. Among recycled aggregate series all they have similar EPI value, however low binder non fly ash series has the highest EPI and also low binder series have slightly higher value than their counterpart. In normal aggregate series, the non fly ash series EPI value is higher than fly ash series. All cases EPI value is higher than control series.

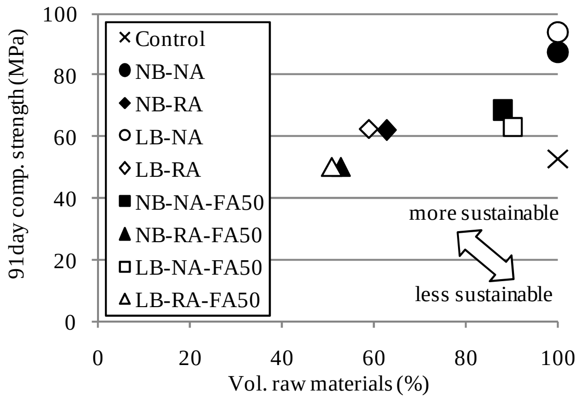

Fig. 9 Compressive strength vs. volume of raw materials

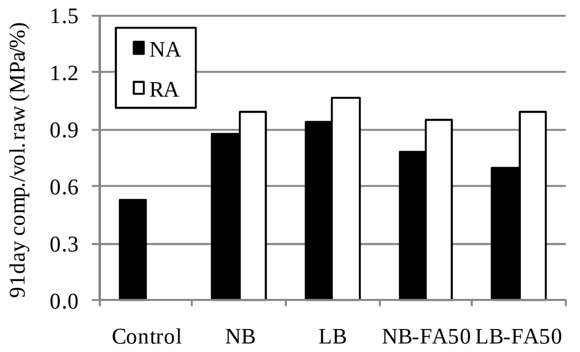

Fig. 10 EPI for compressive strength and raw materials

5. CONCLUSIONS

(1) In this paper the mechanical performance of concrete with variable binder content, composition, and aggregate type was evaluated. It was found that all series except recycled aggregate fly ash mixes gave compressive strength higher than the control series at 7, 28, 56, and 91 days. In general, the strength and quality of the recycled aggregates are believed to be a limiting factor to compressive strength gain. Also there is an increase in time of the compressive strength for fly ash series at higher rate as compared with other concrete mixes.

(2) At 28 and 91 days only non-fly ash series had higher flexural strength. In this case also the strength and quality of the recycled aggregates are believed to be a limiting factor to flexural strength development. The strength development of fly ash series is slightly greater than others.

(3) The environmental impact is less for fly ash series with recycled aggregate, having low CO_2 emissions and replacement of raw materials up to 49% of total volume. The recycled aggregate series show the lowest volume of raw materials, and fly ash series the lowest CO_2 emissions.

(4) From the environmental performance indicators (EPI) can be concluded that fly ash series show the best results when compared with control one.

(5) After analyzing the results obtained and the factors evaluated can be concluded that utilizing recycled materials for developing concrete is a good alternative, due to its good performance compared to normal concrete when evaluating mechanical and environmental performance.

(6) Although this and previous research works have shown the benefits of using this kind of materials, there is still a big concern and general fear of using them mainly because the lack of knowledge and information which is the big barrier for making the concrete a more sustainable industry.

(7) Another big issue is the inclusion of these new technologies into the codes and specifications, which is a slow process, delaying their common acceptance and practice.

(8) It is claimed as well that including low quality recycled aggregate has more risks, but it does not mean than cannot be used as structural concrete.

ACKNOWLEDGEMENT

The authors would like to express their thanks to Mr. Hiromichi Yamashita of the Shibaura Institute of Technology, and all the other members of Kishi-Kato Laboratory who helped in the casting of the concrete series used in this paper.

REFERENCES

[1] Malhotra, V.M. “Making concrete greener with fly ash,” Concrete International, Vol. 21, No. 5, 1999, pp. 61-66.

[2] Meinhold, U., Mellmann, G., and Maultzsch, M., “Performance of high-grade concrete with full substitution of aggregates by recycled concrete,” ACI Special Publication 202: Sustainable Development of Cement and Concrete, 2001, pp. 85-96.

[3] Corinaldesi, V., Tittarelli, F., Coppola, L., and Moriconi, G., “Feasibility and performance of recycled aggregate in concrete containing fly ash for sustainable buildings,” ACI Special Publication 202: Sustainable Development of Cement and Concrete, 2001, pp. 161-180.

[4] “Recommendation of environmental performance verification for concrete structures (draft),” Japan Society of Civil Engineering, 2006.

[5] Nielsen, C.V., “Towards sustainable concrete structures,” Lecture on Sustainability in Concrete and Concrete Structures, University of Tokyo, Japan, January 2009.