- Technical Paper -

EFFECT OF RECYCLED AGGREGATE QUALITY ON VARIATION AND ESTIMATION OF CONCRETE STRENGTH

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ABSTRACT

The effect of recycled aggregate quality on the variation of compressive strength was examined at several water-cement ratios. The variation of recycled aggregate concrete strength was higher than that for normal aggregates but still fell below the JSCE-specified limit, except when combining different recycled aggregate types. An index factor integrating mix proportion and aggregate properties was then proposed to estimate strength and a high degree of correlation was shown both for the experimental results as well as past research results including fly ash concrete.

Keywords: recycled aggregate, concrete strength, coefficient of variation, density, absorption

1. INTRODUCTION

The importance of sustainability is on the rise within the construction industry [1], and with it has come increased consideration of recycling construction and demolition waste in order to conserve natural resources and reduce waste generation. In Japan, although the recycling rate of concrete was up to 96% in 2000 the majority of this was utilized as backfill and sub-grade for road construction [2]. This represents a case of “down-cycling” because it does not reduce consumption of natural resources in construction [3].

Usage of aggregate recycled from demolition waste in new concrete has been investigated in many past research works, where it has been shown that as the quality of recycled aggregate decreases the amount of residual mortar increases and thus the properties of the recycled aggregate become more varied [4]. The interfacial transition zone (ITZ) between the recycled aggregate and new cement mortar is generally weaker than in the case of normal aggregates due to bonding between the new cement mortar matrix, the old attached mortar, and the core aggregate, which results in a decrease in concrete properties and performance including workability, strength, and durability [5,6].

While these works have shown that the usage of recycled aggregates reduces performance, the effect of recycled aggregate quality and variation – particularly at lower quality levels – on the variation in concrete properties has not been clarified. This study therefore focused on investigating this effect in the case of compressive strength, looking at how lower quality recycled aggregates and combinations of normal and recycled aggregates affected the statistical distribution of compressive strength. Next, this study examined the relationship between aggregate properties and strength and proposed an index factor which combines both mix proportion and aggregates properties for estimating the strength of recycled aggregate concrete.

2. EXPERIMENTAL PROGRAM

2.1 Materials

(1) Coarse aggregates

Four different types of coarse aggregates – one normal and three recycled – were used in this investigation. Saturated surface dry (SSD) density and absorption were measured following JIS A 1109 ten times for each aggregate type and the averages and coefficients of variation are given in Table 1. The relationship between density and absorption for all data points is shown in Fig. 1. The density of the recycled aggregates is lower and the absorption higher than the normal aggregates and it can be seen that the variation in density is also larger. The recycled aggregates were also classified according to JIS A 5002, with R1 meeting “low” grade requirements, whereas types R2 and R3 were ranked as “below low” grade due to their absorption properties exceeding the 7% maximum.

Table 1 Properties of coarse aggregates

Type	Density (g/cm^3) [coeff. var.]	Absorption (%) [coeff. var.]	Grade
Normal (N)	2.71 [0.14]	0.78 [9.76]	-
Recycled 1 (R1)	2.45 [0.53]	5.66 [6.32]	Low
Recycled 2 (R2)	2.38 [0.59]	7.53 [3.32]	< Low
Recycled 3 (R3)	2.36 [0.49]	7.91 [4.02]	< Low

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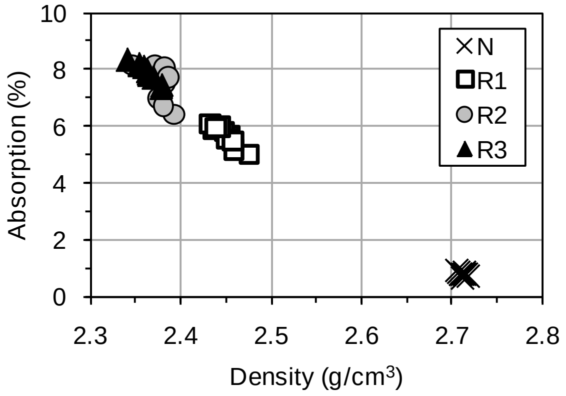

Fig.1 Relationship between density and absorption

(2) Other materials

In addition to coarse aggregates, concrete was prepared using tap water (W), type-I portland cement (C), river sand (S), and air-entraining and super plasticizer admixtures.

2.2 Mix proportions and specimens

Concrete mix proportions and fresh properties are given in Table 2. Three different water-cement ratios (W/C = 30, 50, 70) were examined, along with the four different coarse aggregates types. Two combinations of coarse aggregates (N1-R1, R1-R3), split evenly by volume, were also investigated.

Cylinder specimens were cast for each concrete mix following JSCE-F 552. After casting, molded specimens were covered in plastic wrap and cured in the molds for 24 hours, after which they were removed from the molds and placed in water curing at 20°C.

2.3 Testing and results statistics

Compressive strength testing was conducted 28 days after casting according to JIS A 1108. Following the JSCE "Guideline for Experiment on Materials of Civil Works" (6.3.2C), 30 specimens were tested per series in order to statistically identify the mean and standard deviation of the compressive strength results, and the coefficient of variation was calculated as the percentage ratio of the standard deviation to the mean, which represents the normalized measure of dispersion.

3. VARIATION OF COMPRESSIVE STRENGTH

3.1 Effect of water-cement ratio

The effects of water-cement ratio on compressive strength and coefficient of variation for normal and type-R1 aggregates are shown in Fig. 2. The effect of recycled aggregates on compressive strength was found to decrease as water-cement ratio increases; at water-cement ratio of 30, recycled aggregate concrete has only 76.2% of the strength of normal aggregate concrete, but this percentage increases to 77.5% and 83.9% for water-cement ratios of 50 and 70, respectively.

The effect of recycled aggregate on the coefficient of variation of the compressive strength results also varies depending on the water-cement ratio. The coefficient of variation for normal aggregate concrete at water-binder ratio 30 is actually higher than that of the recycled aggregate concrete at the same water-binder ratio. This may be related to the compressive failure behavior of high-strength concrete, rather than the aggregate type. In addition, the coefficient of variation for the normal aggregate concrete at water-cement ratio 30 barely falls below 5%. According to the JSCE "Guideline for Experiment on Materials of Civil Works" (3.10.3B), if the coefficient of variation exceeds 5% then the overdesign factor needs to be increased beyond the base factor of 1.1. It can be seen that the coefficients of variation for the recycled aggregate concretes, although higher than that of the normal aggregate concretes at water-cement ratios 50 and 70, still fall below the 5% threshold. Furthermore, the coefficients of variation for the recycled aggregate concretes remain similar regardless of the water-cement ratio or strength level.

3.2 Effect of aggregate type

Fig. 3 shows the compressive strength and coefficient of variation results by varying aggregate type at water-cement ratio of 50. While the normal aggregate concrete has a 28-day compressive strength of 41.9 MPa, the strengths of the recycled aggregate concretes are generally similar and fall between 32.7 MPa (for type-R2) and 28.8 (for type-R3). This result shows that the varying properties of the recycled

Table 2 Concrete mix proportions and fresh properties

<table>
<tr><th rowspan="2">Series</th><th colspan="2">Material ratios (%)</th><th colspan="7">Mix proportions (kg/m^3)</th><th rowspan="2">Slump (cm)</th><th rowspan="2">Air content (%)</th></tr>
<tr><th>W/C</th><th>s/a</th><th>W</th><th>C</th><th>S</th><th>N</th><th>R1</th><th>R2</th><th>R3</th></tr>
<tr><td>30-N</td><td rowspan="2">30</td><td rowspan="2">39</td><td>177</td><td>589</td><td>596</td><td>989</td><td>-</td><td rowspan="4">-</td><td rowspan="5">-</td><td>14.0</td><td>5.8</td></tr>
<tr><td>30-R1</td><td>171</td><td>569</td><td>609</td><td>-</td><td>914</td><td>14.0</td><td>6.9</td></tr>
<tr><td>50-N</td><td rowspan="6">50</td><td>43</td><td>177</td><td>353</td><td>742</td><td>1042</td><td>-</td><td>13.0</td><td>5.5</td></tr>
<tr><td>50-R1</td><td>45</td><td>177</td><td>354</td><td>785</td><td rowspan="3">-</td><td>897</td><td>13.5</td><td>6.5</td></tr>
<tr><td>50-R2</td><td>43</td><td>166</td><td>332</td><td>771</td><td rowspan="2">-</td><td>932</td><td>9.5</td><td>5.9</td></tr>
<tr><td>50-R3</td><td>45</td><td>176</td><td>352</td><td>787</td><td rowspan="5">-</td><td>866</td><td>14.5</td><td>5.3</td></tr>
<tr><td>50-N-R1</td><td>45</td><td>175</td><td>350</td><td>789</td><td>503</td><td>453</td><td>-</td><td>13.0</td><td>6.6</td></tr>
<tr><td>50-R1-R3</td><td>43</td><td>177</td><td>353</td><td>749</td><td>-</td><td>466</td><td>448</td><td>13.5</td><td>5.8</td></tr>
<tr><td>70-N</td><td rowspan="2">70</td><td rowspan="2">47</td><td>179</td><td>256</td><td>857</td><td>1001</td><td>-</td><td rowspan="2">-</td><td>13.0</td><td>5.5</td></tr>
<tr><td>70-R1</td><td>187</td><td>267</td><td>841</td><td>-</td><td>887</td><td>13.5</td><td>4.8</td></tr>
</table>

aggregates do not have a large effect on the compressive strength. The coefficient of variation results are also similar, with the normal aggregate concrete at 2.9% while the coefficients of variation for the recycled aggregate concretes range from 3.9% (for type-R1) to 4.3% (for type-R2). Similar to the results by water-cement ratio, although the variation is higher for the recycled aggregate concretes the values still fall below the 5% limit established by JSCE.

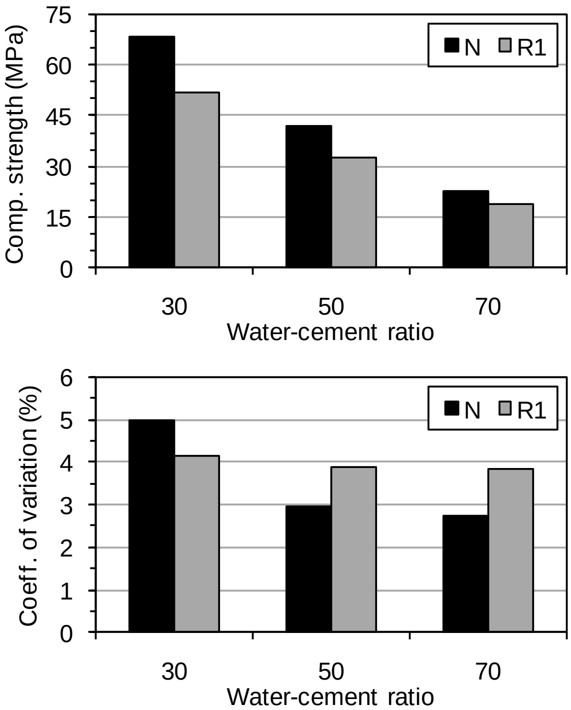

Fig.2 Effect of water-cement ratio on compressive strength (top) and coefficient of variation (bottom)

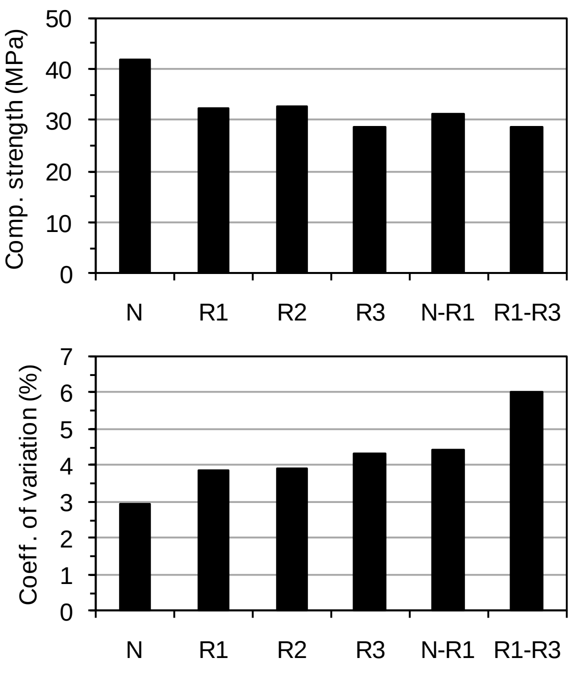

Fig.3 Effect of aggregate type on compressive strength (top) and coefficient of variation (bottom) at water-cement ratio 50

3.3 Effect of combining aggregate types

The effects of combining different aggregate types on compressive strength and coefficient of variation are also shown in Fig. 3. The combination N-R1 has strength similar to concrete with just type-R1 but is 25.3% less than the strength of the normal aggregate concrete. This appears to indicate that the recycled aggregate quality played a limiting factor, even though it was used in equal volume as the normal aggregate. For the combination R1-R3, the strength is similar to that of the concrete containing just type-R3 but only slightly less than that of concrete containing just type-R1. Again, this seems to suggest that the lowest-grade recycled aggregate has a limiting effect.

In contrast, the combination N-R1 has a slightly higher coefficient of variation than either of the concretes containing only one type of aggregate. The value does, however, fall below 5%. On the other hand, the combination R1-R3 has a much higher coefficient of variation than either of the concretes with only one type of recycled aggregate, and this value exceeds the 5% limit. Therefore, although combining aggregate types may not have a detrimental effect on the compressive strength the coefficient of variation may increase significantly. In the case of the combination N-R1, the higher quality of the normal aggregates may have served to help reduce the variation from combination, whereas combining two low-quality recycled aggregate types may amplify the variation.

4. STRENGTH ESTIMATION INDEX FACTOR

If the variation of strength when using recycled aggregates falls within acceptable limits, as was shown for all cases except the combination of different recycled aggregate types, then the estimation of recycled aggregate concrete strength may be achieved simply by understanding how much strength reduction occurs as a function of the aggregate quality. Aggregate quality can be quantified by the density and absorption, as shown in Fig. 1. However, the estimation of concrete strength also needs to take into account the mortar mix properties – specifically, the mix proportioning.

4.1 Mix proportion-strength relationship

The relationship between mix proportions and compressive strength was examined using the cement-water ratio. Fig. 4 shows the results for all experimental series, and it can be seen that strength linearly increases as the cement-water ratio increases. In this case, the strength is represented only by the mix proportion and doesn’t take into account the aggregate properties; however, it can be seen that a good linear correlation (R^2=0.8689) between just the cement-water ratio and compressive strength can be achieved.

4.2 Aggregate property-strength relationship

The relationships between aggregate properties and compressive strength are shown in Fig. 5 for weighted density and Fig. 6 for weighted absorption. The aggregate properties were weighted by multiplying the properties of the utilized aggregates by their aggregate volume ratio; this is intended to provide representation for concretes with mixed aggregate types. In addition, for this relationship there is no consideration of the effect of the mix proportions so only the results from mixes with the same cement-water ratio (water-cement ratio of 50) are shown.

The relationship between the weighted density and compressive strength can be represented with a direct linear relationship, whereas that of the weighted absorption and compressive strength can be represented with an inverse linear relationship. In both cases, the correlation is lower than that of the cement-water ratio/compressive strength case.

4.3 Index factor for strength estimation

The relationships between the aggregate properties and the compressive strength considered the strength only in terms of a single aggregate property; however, as was shown in Fig. 1, the density and absorption are also related and so strength estimation should take into account both properties simultaneously. However, focusing only on the aggregate properties neglects the contribution of the cement-water ratio. Therefore, the following index factor (Eq. 1) was proposed by Pardo [7] to combine all three variables for estimating the compressive strength of recycled aggregate concrete.

$$IF = \left(\frac{C}{W}\right) \times \left(\frac{D_W}{D_{abs}}\right) \times \left(1 - \frac{A_W}{100}\right) \qquad (1)$$

where,

IF : index factor
C/W : cement-water ratio
D_w : weighted density (g/cm^3)
D_{abs} : absolute density (g/cm^3)
A_w : weighted absorption (%)

For this calculation, the absolute density is set as that of the aggregate with the highest density (normal aggregate in the case of this investigation).

The relationship between the index factor and compressive strength for all series is shown in Fig. 7. As the index factor increases the compressive strength also increases linearly with a very high correlation (R^2=0.9629). Therefore, it can be clearly seen that the index factor provides the best estimation of recycled aggregate concrete compressive strength by considering both aggregate and mix proportion properties. However, the experimental results used here consider only normal portland cement concrete. Some past research results have reported that the usage of fly ash has a beneficial effect when combined with recycled aggregates through improvement of pore structure and bonding [8,9], so results of an investigation considering fly ash and recycled aggregate will also be examined.

4.4 Index factor considering fly ash concrete

Pardo [7] investigated the properties of concrete combining fly ash with full and partial recycled aggregate usage at several water-binder ratios. The experimental variables are summarized in Table 2.

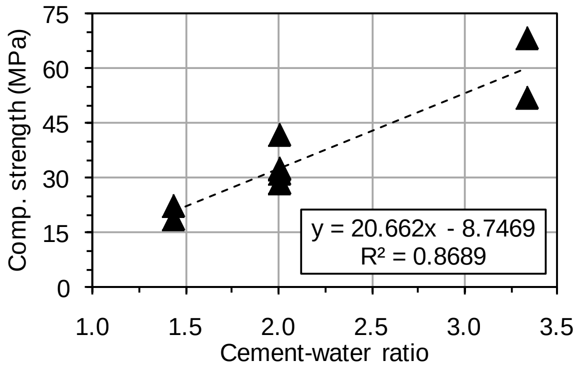

Fig.4 Relationship between cement-water ratio and compressive strength

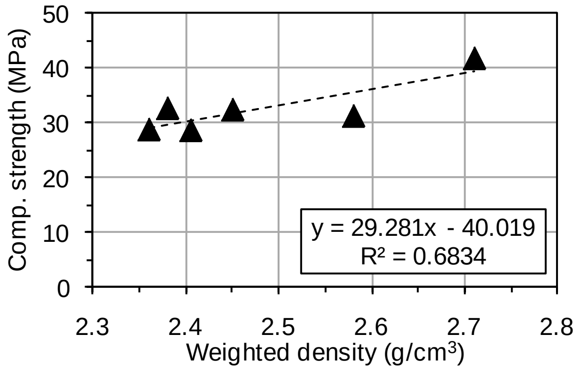

Fig.5 Relationship between weighted density and compressive strength

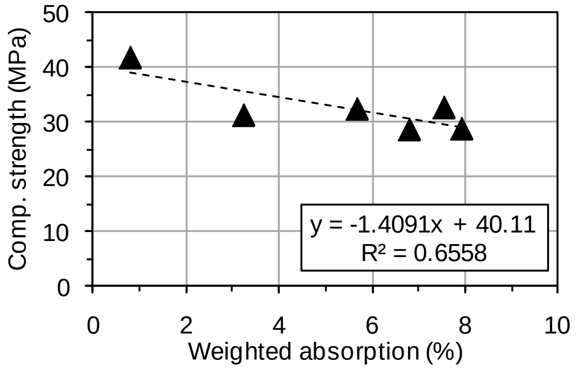

Fig.6 Relationship between weighted absorption and compressive strength

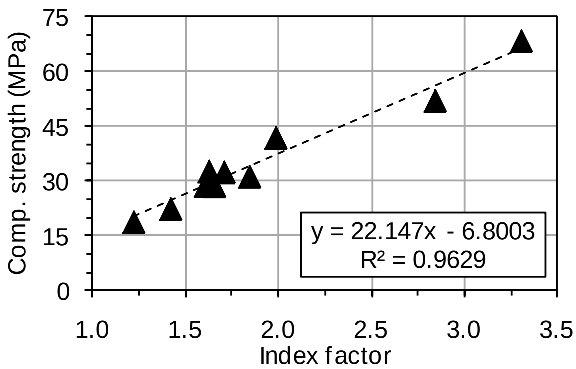

Fig.7 Relationship between index factor and compressive strength

Table 2 Experimental variables for investigation considering fly ash and recycled aggregates

Mix proportions	
Water-binder ratio	0.3, 0.375, 045
Water content (kg/m^3)	135
Normal aggregate properties	
Density (g/cm^3)	2.72
Absorption (%)	0.5
Recycled aggregate properties	
Replacement ratio	0%, 50%, 100%
Density (g/cm^3)	2.43
Absorption (%)	5.81
Grade	Low
Fly ash properties	
Classification	JIS type-II
Replacement ratio	50%

Other materials used in concrete making, specimens, preparations, curing, testing procedures and other factors for the concrete series utilizing fly ash and recycled aggregates were all the same as those in this experimental program.

The relationship between the index factor and 28-day compressive strength for concrete with 50% fly ash replacement is shown in Fig. 8. Just as in the case of non-fly ash concrete introduced previously, a strong linear relationship (R^2=0.9585) can be seen between the index factor and the compressive strength. This result demonstrates that the proposed index factor may also be applied to concretes with fly ash, which is especially important considering the usefulness of fly ash and recycled aggregates together for reducing environmental impacts such as CO_2 emissions, resource consumption, and waste generation.

4.5 Index factor for past research results

Finally, the applicability of the index factor was examined by applying it to results reported in literature [6,10,11]. As summarized in Table 3, these cover 18 different cases from three separate investigations. Fig. 9 shows the relationship between the index factor and compressive strength for the past research results. For each of the three investigations a high correlation can be seen; for Dhir et al. and Kou et al., the R^2 value exceeds 0.98. This result strongly demonstrates the applicability of the proposed index factor to research results obtained at other institutions using other methods and materials.

5. CONCLUSIONS

(1) The effect of recycled aggregate on compressive strength variation was fairly similar regardless of water-cement ratio. Although variation for recycled aggregate concrete was higher than for normal aggregate concrete, it still fell below the JSCE-specified limit of 5% and thus the overdesign factor does not need to be increased.

(2) At the same water-cement ratio, varying the type of recycled aggregate did not greatly affect the compressive strength. Furthermore, the variation of the recycled aggregate concrete was higher than for normal aggregate concrete but within the JSCE-specified limit.

(3) When combining aggregate types, it was seen that the lowest-grade aggregate limited the strength level but the variation in strength was greater than when either of the aggregate types was utilized alone. When combining two different recycled aggregate types, the variation exceeded the JSCE-specified limit

(4) Linear relationships between both mix proportion (cement-water ratio) and weighted aggregate (density, absorption) properties and 28-day compressive strength could be seen, with stronger correlation for the cement-water ratio than for density or absorption.

(5) An index factor integrating all three of the afore-mentioned properties was proposed, and a very strong linear correlation between this index factor and the compressive strength of recycled aggregate concrete was shown. This result demonstrates the usefulness of the index factor as a means for estimating strength by considering both mix proportion and aggregate properties.

(6) The applicability of the index factor was examined using results from another investigation combining fly ash and recycled aggregates as well results from literature. In both cases, very strong linear correlation could be seen between the index factor determined from the experimental cases and the compressive strength, thus verifying the applicability of the proposed index factor to other material and experimental conditions.

(7) Although the proposed index factor was shown to provide a good estimation of compressive strength, this examination did not consider other performances such as durability variation, which is a key vulnerability of recycled aggregate concrete. In addition, the fresh properties were set as uniform across the different mixes, but this required varying the sand-aggregate ratio and amount of admixtures. Future research needs to consider both the variation in fresh properties and durability – particularly when mixing different types of low grade recycled aggregates.

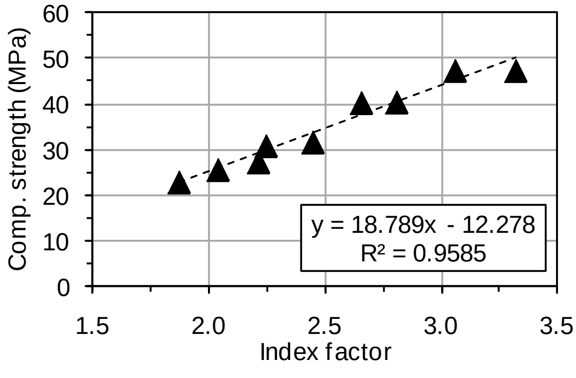

Fig.8 Relationship between index factor and compressive strength considering fly ash concrete

Table 3 Summary of past research results

Source	W/C	D_w (g/cm^3)	A_w (%)	Comp. strength (MPa)
Dhir et al, 1999	0.29	2.60	2.50	71.5
Dhir et al, 1999	0.32	2.41	5.05	62.5
Dhir et al, 1999	0.36	2.60	2.50	60.0
Dhir et al, 1999	0.40	2.43	5.90	40.1
Dhir et al, 1999	0.44	2.41	5.05	52.0
Dhir et al, 1999	0.45	2.60	2.50	52.0
Otsuki et al, 2003	0.40	2.44	4.50	44.0
Otsuki et al, 2003	0.55	2.41	5.13	30.0
Otsuki et al, 2003	0.55	2.44	4.50	33.0
Otsuki et al, 2003	0.55	2.47	3.58	32.0
Otsuki et al, 2003	0.55	2.45	6.46	32.0
Otsuki et al, 2003	0.55	2.54	2.68	30.0
Otsuki et al, 2003	0.59	2.36	6.71	39.0
Otsuki et al, 2003	0.60	2.58	5.50	32.5
Kou et al, 2008	0.40	2.53	3.89	58.5
Kou et al, 2008	0.45	2.53	3.89	52.1
Kou et al, 2008	0.50	2.53	3.89	43.4
Kou et al, 2008	0.55	2.53	3.89	38.1

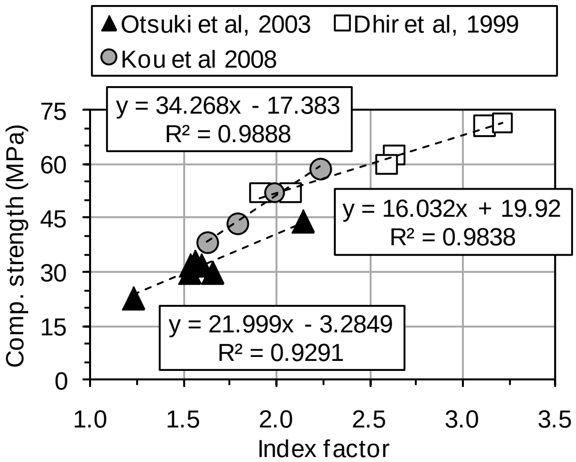

Fig.9 Relationship between index factor and compressive strength for past research results

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REFERENCES

[1] Horvath, A. and Matthews, H.S., "Advancing sustainable development of infrastructure systems," Journal of Infrastructure Systems, Vol. 10 No. 3, 2004, 77-78.

[2] "MLIT Annual Report," Ministry of Land, Infrastructure, and Transportation, 2009. (in Japanese)

[3] Mehta, P.K., "Reducing the environmental impact of concrete," Concrete International, Vol. 23 No. 10, 2001, 61-66.

[4] Lo., C.Y., Kotrayothar, D., Tam, V.W.Y., Loo, Y.C., "Comparison of recycled and natural aggregate properties," 3rd ACF International Conference, 2008, 450-454.

[5] Poon, C.S., Shui, Z.H., Lam, L., "Effect of microstructure of ITZ on compressive strength of concrete prepared with recycled aggregates," Construction and Building Materials, Vol. 18, 2004, 461-468.

[6] Otsuki, N., Miyazoto, S., Yodsudjai, W., "Influence of recycled aggregate on interfacial transition zone, strength, chloride penetration and carbonation of concrete," Journal of Materials in Civil Engineering, Vol. 15 No. 5, 2003, 443-451.

[7] Pardo, G., "Design methodology for green concrete containing high volume of recycled materials," Master thesis, Deptartment of Civil Engineering., The University of Tokyo, Japan, 2010.

[8] Corinaldesi, V., Tittarelli, F., Coppola, L., Moriconi, G., "Feasibility and performance of recycled aggregate in concrete containing fly ash for sustainable buildings," ACI SP-202 Sustainable development of cement and concrete, 2001, 161-180.

[9] Ann, K.Y., Moon, H.Y., Kim, Y.B., Ryou, J., "Durability of recycled aggregate concrete using pozzolanic materials," Waste Management, Vol. 29, 2008, 993-999.

[10] Kou, S.C., Poon, C.S., Chan, D., "Influence of fly ash as a cement addition on the hardened properties of recycled aggregate concrete," Materials and Structures, 2008, 1191-1201.

[11] Dhir, R.K., Limbachiya, M.C., Leelawat, T., "Suitability of recycled concrete aggregate for use in BS5328 designated mixes," Structures and Buildings, Vol. 134 No. 3, 1999, 257-274.