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BASIC STUDY ON ADEQUATE METHODS OF USING LOW QUALITY AGGREGATE

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SYNOPSIS

It is very important for the concrete industry to find adquate methods of using low quality aggregate, because the quality of aggregate has become lower and recently it is not easy to obtain proper aggregate for concrete. In this experiment, it is examined whether low quality aggregate can be effectively used by the following two methods. One method is to adjust mix proportion of concrete in order to cover the defect of using low quality aggregate. In another method, good quality aggregate is mixed with low quality aggregate in order to improve the average characteristics of aggregate. Although the problem is not solved completely by these methods, there seems to be the possibility of using the low quality aggregate by properly adapting these methods according to the required properties of concrete.

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1. INTRODUCTION

Aggregate for concrete should be selected carefully because there occurs many problems such as expansion of concrete caused by alkali-aggregate reaction and corrosion of steel caused by chloride contained in sea sand. On the other hand, the quality of aggregate has become lower and recently it is not easy to obtain aggregate having proper physical qualities such as specific gravity and absorption. Therefore, it is also desired for concrete industry to establish adequate methods of using low quality aggregate contrary to the careful selection of aggregate.

Impregnation with resin seems to be one of the methods to improve physical properties of aggregate, but this method is not necessarily practical at this stage. Since it is very difficult to improve the quality of aggregate itself, it is thought as the second best policy to cover the defect of using low quality aggregate by other materials. In this experiment, it is examined whether low quality aggregate can be effectively used by the following two methods. One method is to adjust mix proportion of concrete in order to strengthen matrix of concrete. In another method, good quality aggregate is mixed with low quality aggregate in order to improve the average properties of aggregate.

The object of this experiment is only coarse aggregate, because it has been pointed out that the bad influence of using low quality coarse aggregate is conspicuous comparing with using low quality fine aggregate. According to the previous experimental results, gravel is composed of various stony particles, and properties of concrete strongly depend upon the variety of particles. It is very difficult, therefore, to draw the conclusion about the relation between physical properties of gravel and concrete, so that crushed stone was only used as coarse aggregate of concrete in this experiment.

2. OUTLINE OF EXPERIMENT

A large variety of crushed stones, as many as 15, from Iwate and Aomori Prefecture were used in this experiment. Table 1 shows their physical and mechanical properties. Compressive strength and static modulus of elasticity were measured using cylindrical specimen (ϕ30X60mm) which was cored from mother rock. Drying shrinkage of some crushed stones was measured using cored specimen.

If aggregate exhibiting specific gravity under 2.50 and absorption beyond 3% is defined as "low quality aggregate", six crushed stones correspond to this category. Other four crushed stones have specific gravity beyond 2.50, but thier absorption is beyond 3%. It is obviously from percentage of solid volume that particle shape differs with each crushed stone. Although this difference of shape seems to affect properties of concrete, the influence is not considered in this paper.

All crushed stones were prepared in order to have the same grading distribution and a maximum size of 25mm. The same river sand (specific gravity : 2.54, absorption : 3.3%) from Shizukuishi River and normal portland cement were used in all concrete and mortar specimens.

The mix proportion of concrete is shown in Table 2. In order to clarify the

Table 1 Used crushed stone

No	Specific gravity	Absorption (%)	Abrasion (%)	Soundness (%)	Percentage of solid volume (%)	Compressive strength (kgf/cm^2)	Dynamic elastic modulus ($x10^5$ kgf/cm^2)
1	2.28	10.97	34.25	33.09	60.8	676	0.96
2	2.34	11.35	35.30	61.10	58.3	253	0.92
3	2.39	5.31	18.08	11.15	58.5	1,120	3.54
4	2.42	7.87	33.41	57.12	60.2	317	1.37
5	2.48	6.02	13.21	5.78	59.0	1,094	3.99
6	2.48	5.26	14.58	14.17	56.7	922	3.01
7	2.50	4.53	24.08	18.75	58.4	1,061	3.25
8	2.54	4.61	26.27	6.88	59.8	962	3.66
9	2.57	3.31	14.90	2.20	58.0	1,613	4.67
10	2.62	4.58	26.48	12.10	58.3	990	3.01
11	2.65	2.45	16.98	9.27	54.4	1,330	5.48
12	2.71	0.78	10.88	6.22	57.4	1,404	7.99
13	2.73	1.41	14.50	3.60	57.2	2,341	7.78
14	2.91	0.58	5.70	2.30	58.6	3,105	9.94
15	2.95	0.76	8.30	7.72	56.7	2,206	9.93

Table 2 Mix proportion of concrete

Water-cement ratio W/C(%)	Unit quantity of material			
	Water $W(kg/m^3)$	Cement $C(kg/m^3)$	Fine aggregate $S(kg/m^3)$	Coarse aggregate $G(l/m^3)$
30	194	647	553	386
40		488	684	
50		388	762	
60		323	814	
70		297	851	
100		194	918	

effect of coarse aggregate upon properties of concrete over a wide range of mix proportion, very rich mixture (W/C=30%) and lean mixture (W/C=100%) were chosen together with normal mixture. The weight of water and the volume of coarse aggregate per unit volume of concrete were kept constant throughout so as to simplify the comparison among concrete specimens made with various crushed stones. Mortar specimens were also made according to mix proportion shown in this table, excluding coarse aggregate..

All kinds of crushed stones and mix proportions described above were used in the experiment which examined the relation between mix proportion and mechanical properties of concrete. In the case of other experimental purposes, crushed stones and mix proportions were chosen from them according to each purpose.

Cylindrical specimen (ϕ10X20cm) was used for the mechanical tests of concrete such as compressive strength, splitting tensile strength and modulus of elasticity, and prism specimen (10X10X40cm) for the tests of drying shrinkage and freezing and thawing. Specimen was cured in water for 28 days. After curing, specimen for drying shrinkage test was dried in an atmosphere at 20℃, with relative humidity of 60%. The test on durability was continued until 300 cycles of freezing and thawing in air. The range of temperature was from -10℃ to +20℃.

3. POSSIBILITY OF EFFECTIVE USE OF LOW QUALITY AGGREGATE BY ADJUSTING MIX PROPORTION

3.1 Uniformity of Crushed Stone

In this experiment, crushed stone was selected as coarse aggregate for convenient analysis because variety of particles in crushed stone was expected to be smaller than that in gravel.

In order to confirm the uniformity of crushed stone, one hundred particles with particle size of 15~20mm were randomly collected from each kind of crushed stone, and their basic properties, specific gravity and absorption, were measured one by one. Figure 1 shows the examples of the measurement in the distribution of specific gravity of comparatively high and low quality of crushed stones, together with the examples of gravel having almost same average specific gravity.

Specific gravity of particles in gravel varies widely, especially in low quality gravel. On the other hand, the distribution of specific gravity in crushed stone is narrow and the standard deviation calculated on the assumption that the distribution of each data is a normal curve is small, so that the uniformity of crushed stone is obviously better than that of gravel. This suggests that the defect of concrete coming from ununiformity of aggregate is not a serious problem in case of crushed stone compared with gravel, and that the relation between properties of aggregate and concrete can be examined by using only the average value of properties of crushed stone.

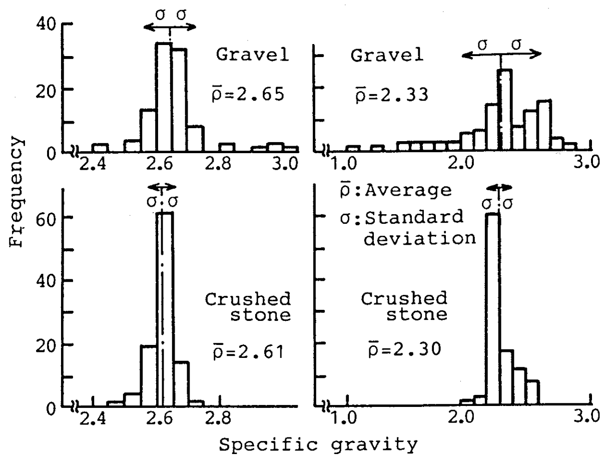

Fig.1 Distribution of specific gravity

Figure 2 shows the relation between specific gravity and absorption of 1,500 particles on semilogarithmic graph. Although there is a certain tendency on the whole, it is difficult to relate the two by a single straight line. This means that the relation between specific gravity and absorption of each kind of crushed stone depends on property of its mother rock, and that the relation between properties of crushed stone and concrete varies to some extent with the index of crushed stone, specific gravity or absorption.

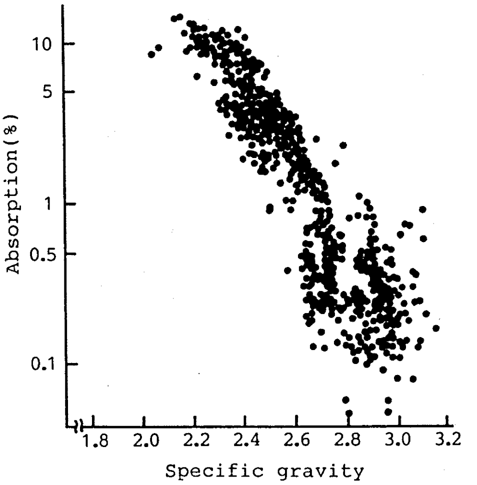

Fig.2 Relation between specific gravity and absorption

3.2 Relation between Properties of Crushed Stone and Concrete

The quality of aggregate is generally judged by its physical properties such as specific gravity and absorption. However, there seems not to be the precise definition of which aggregate is classified as low quality one according to the range of these physical properties. The aggregate which can not ensure the desired properties of concrete should be defined originally as low quality aggregate. It thus appears that the relation between properties of aggregate and concrete should be clarified fully in order to establish the definition of low quality aggregate according to properties of aggregate.

Figure 3 shows, as an example of this examination, the relation between properties of crushed stone and compressive strength of concrete in case of water-cement ratio of 50%. The quality standards of crushed stone are also indicated in this figure. Although there is obvious scattering of the data, it is clear that the lower the quality of crushed stone is, the less is the compressive strength of concrete. Considering the quality standards except for percentage of abrasion, concrete made with crushed stone whose properties meet the standard requirements can keep adequate compressive strength. On the other hand, compressive strength of concrete made with crushed stone below the standards basically tends to be low, so that the standards can be a useful indicator for judging the quality of aggregate.

However, there are some exceptions in the data, such as in the relation between absorption of crushed stone and compressive strength of concrete. Compressive strength of concrete using crushed stone, whose absorption is off the standards of 3% but under 5%, can compare with concrete using good quality crushed stone. This means that the standards now in use are not always proper, and that a re-examination of the standards is necessary. If it is possible to ease the standards, the range of crushed stone which can be used in practice will become wider. It is necessary, of course, to examine in detail the effect of properties of crushed stone not only on compressive strength but also on other mechanical properties and durability of concrete in order to ease the standards.

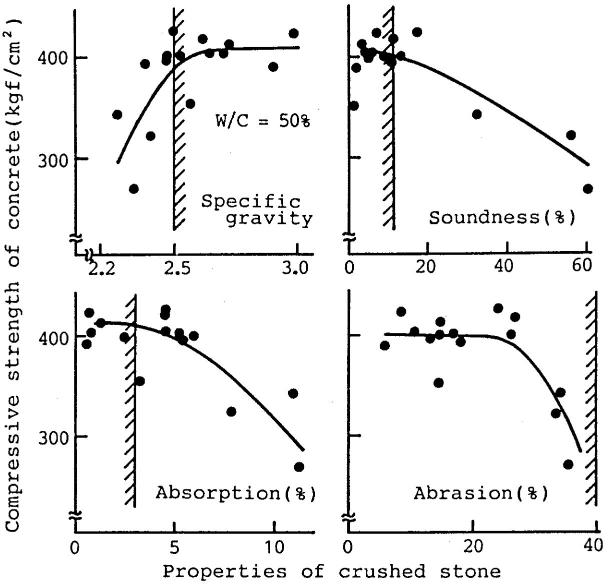

Fig.3 Relation between properties of crushed stone and compressive strength of concrete

3.3 Strength of Concrete

Although the definition of low quality aggregate still leaves room for discussion, crushed stone exhibiting specific gravity under 2.50 is defined here as "low quality aggregate". Crushed stones No.1 to No.6 in Table 1 correspond to this category. Concretes using crushed stone No.1 to No.4 among them are compared with concretes made with crushed stone having specific gravity beyond 2.50 (No.7 ~ No.15 in Table 1).

Figure 4 shows the relation between cement-water ratio and compressive strength

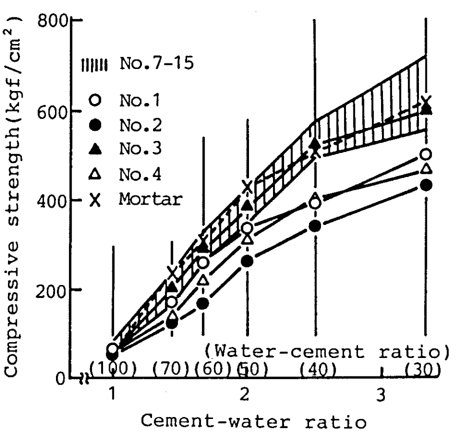

Fig.4 Relation between cement-water ratio and compressive strength of concrete

of concrete. The extent of hatched lines in this figure collectively indicates compressive strength of concrete made with crushed stone having specific gravity beyond 2.50.

Although the quality of crushed stone which meet the standard requirement of specific gravity differs considerably, as shown in Table 1, the difference of compressive strength of concrete made with these crushed stones is extremely small.

The relation between compressive strength of crushed stone itself and concrete made with this stone is shown in Fig.5.

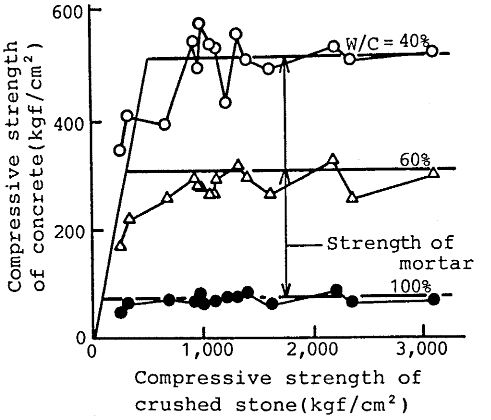

Fig.5 Relation between compressive strength of crushed stone and concrete

It is obvious that compressive strength of concrete cannot surpass the strength of mortar, even if the strength of crushed stone is very high. This suggests that compressive strength of concrete is not determined by the strength of crushed stone but by the strength of mortar when good quality crushed stone is used.

On the other hand, compressive strength of concrete made with low quality crushed stone is less than the strength of mortar, because the strength of crushed stone is low and the failure of crushed stone precedes the failure of mortar when the concrete is under compression. This tendency is remakable in the region of low water-cement ratio, so it seems to be impossible to use such crushed stone for concrete where high strength is desired.

The difference between concrete made with low quality crushed stone and concrete made with high quality crushed stone is small in terms of compressive strength, under the condition that water-cement ratio is extremely large. Low quality crushed stone can be effectively used in cases of such mix proportions.

A certain high strength of concrete will be obtained by selecting proper mix proportion, as is shown in Fig.4, even if low quality crushed stone is used. In order to obtain concrete strength of 300kgf/cm^2, for example, water-cement ratio is about 60% in the case of using crushed stone which meet the standard requirement of specific gravity. The same strength of concrete can be obtained by selecting water-cement ratio of 45 ~ 55% when low quality crushed stone is used. This difference between water-cement ratios is obviously large, and cement content in the mix proportion of concrete made with low quality crushed stone is so large that high cost of the concrete is to be feared. However, using low quality crushed stone is possible to be more economical, under certain circumstances, than buying high quality crushed stone from a distance.

The following models were assumed in order to generalize the relation among quality of crushed stone, mix proportion and compressive strength of concrete. In these models, concrete is considered to be a material composed of mortar and coarse aggregate as is shown in Fig.6. The same stress occurs within mortar and coarse aggregate in case of the series model and the same strain in case of the parallel model when the concrete is under compression.

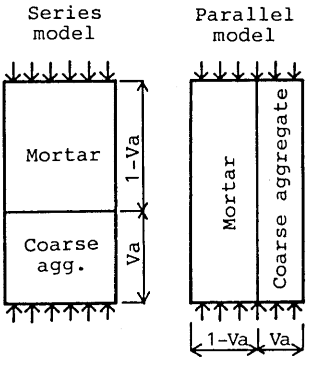

Fig.6 Analytic model

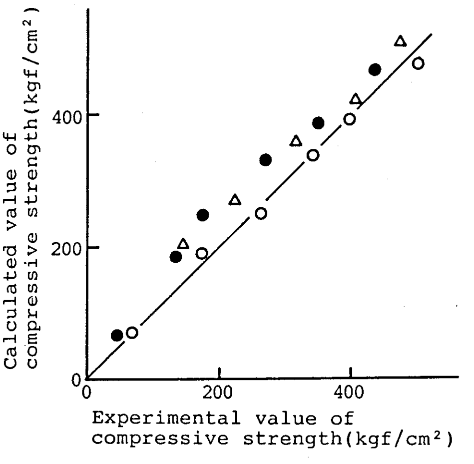

Fig.7 Examination of composite equation on compressive strength

According to the examination on the models in case of static modulus of elasticity of concrete, the series model is useful for $E_a > E_m$ and the parallel model for $E_a < E_m$. If the same relationship is established in case of compressive strength of concrete, the following composite theory of compressive strength will be obtained.

$$F_c = k\{1-(1-E_a/E_m)V_a\}F_m + (1-k)F_m \qquad (1)$$

$k=0$ for $E_a > E_m$

$k=1$ for $E_a < E_m$

F_c: compressive strength of concrete (kgf/cm^2)

F_m: compressive strength of mortar (kgf/cm^2)

E_a: static modulus of elasticity of coarse aggregate ($\times 10^5$kgf/cm^2)

E_m: static modulus of elasticity of mortar ($\times 10^5$kgf/cm^2)

V_a: coarse aggregate volume concentration

The above equation means that compressive strength of concrete should be equal to compressive strength of mortar for $E_a > E_m$, and the propriety of this estimation is confirmed from Fig.4. On the other side, the propriety of the above equation for $E_a < E_m$ is examined in Fig.7 and the calculated values of compressive strength of concrete almost agree with experimental values.

Factors included in the equation such as F_m, E_m and E_a are not generally measured in actual concrete works, so that there is a practical difficulty with this equation. These factors can be related with mix proportion of concrete or property of aggregate as follows, based on experimental results.

$$F_m = 256(C/W) - 114 \quad (2)$$

$$E_m = 0.59(C/W) + 1.06 \quad (3)$$

$$E_a = 14.6\rho_a - 32.9 \quad (4)$$

C/W: cement-water ratio

ρ_a: specific gravity of coarse aggregate

Figure 8 shows the relation among cement-water ratio, specific gravity of coarse aggregate and compressive strength of concrete, obtained by substituting above equations into equation (1).

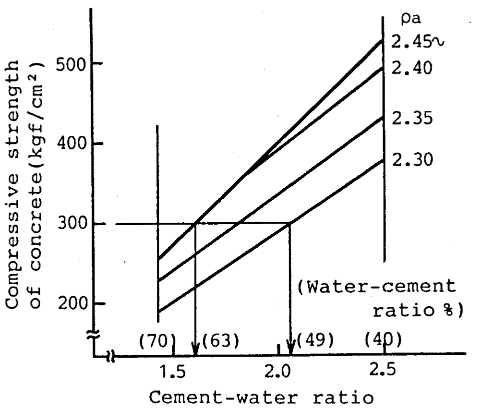

Fig.8 Estimation of compressive strength of concrete

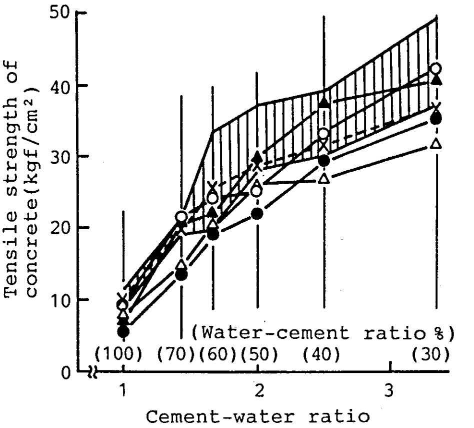

Fig.9 Relation between cement-water ratio and tensile strength of concrete

It can be read off this figure, for example, that compressive strength of concrete of 300kgf/cm^2 can be obtained by selecting water-cement ratio of 63% in case of using coarse aggregate whose specific gravity is 2.40. If specific gravity of coarse aggregate is 2.30, the same strength of concrete can be obtained by selecting water-cement ratio of 49%. Although this figure is proper to this experiment, it is expected that useful procedure to select mix proportion considering quality of each aggregate can be obtained by accumulation of experiments.

Figure 9 shows the relation between cement-water ratio and splitting tensile strength of concrete.

The difference of tensile strength due to kind of crushed stone is larger than that of compressive strength and tensile strength of a large majority of concretes exceeds that of mortar, in case of using crushed stone which meets the standard requirement of specific gravity. Crushed stone, as described above, does not increase compressive strength of matrix (mortar) even if high quality, but crushed stone has a role to reinforce matrix in case of tensile strength. This role seems to depend not only on physical and mechanical properties but also on shape of crushed stone.

Tensile strength of concrete made with low quality crushed stone is relatively small, but the tendency is not obvious, compared with compressive strength, such as there exist examples having larger tensile strength than mortar. These examples also shows the difficulty to investigate the relation between properties of crushed stone and tensile strength of concrete. Figure 9 also indicates that a certain high tensile strength will be obtained by proper selection of mix proportion even if low quality crushed stone is used.

The relation between compressive and tensile strength of concrete is shown in Fig.10.

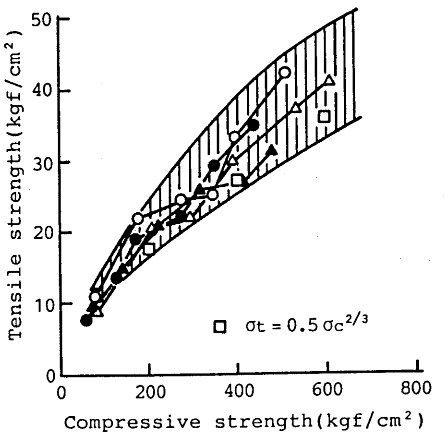

Fig.10 Relation between compressive and tensile strength of concrete

According to the Standard Specification for Design and Construction of Concrete Structures by Japan Society of Civil Engineers (JSCE), tensile strength of normal concrete may be obtained in accordance with following equation, based on compressive strength, in the case where tensile strength tested is not available.

$$\sigma_t = 0.5\,\sigma_c^{2/3} \qquad (5)$$

σ_t: tensile strength of concrete (kgf/cm^2)

σ_c: compressive strength of concrete (kgf/cm^2)

The values calculated according to this equation are shown in the figure. This equation seems to be proper for predicting tensile strength, because the values are plotted within the extent of hatched line in this figure which indicates collectively strength of concrete made with crushed stone having adequate specific gravity. Concretes made with low quality crushed stone are also located within the extent so that it seems to be quite all right to predict tensile strength of concrete made with such crushed stone according to the equation by the Standard Specification. This figure also means that brittleness index expressed by the ratio of compressive and tensile strength of concrete does not depend on the quality of crushed stone.

3.4 Elastic Properties of Concrete

Static and dynamic modulus of elasticity of concrete are shown in Fig.11 and 12

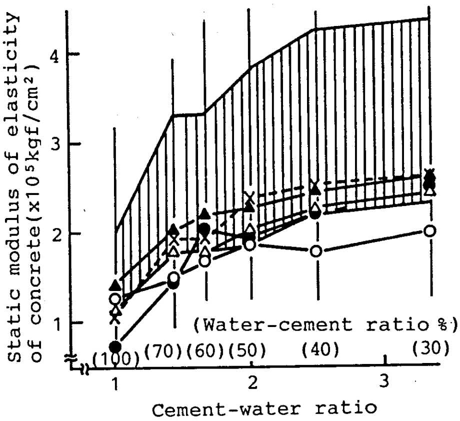

Fig.11 Relation between cement-water ratio and static modulus of elasticity of concrete

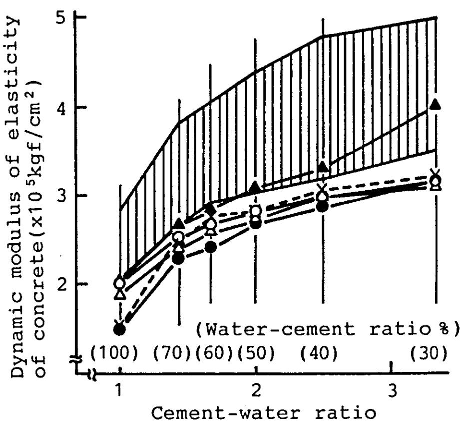

Fig.12 Relation between cement-water ratio and dynamic modulus of elasticity of concrete

respectively.

Modulus of elasticity of concrete made with crushed stone having adequate specific gravity is strongly influenced by the quality of crushed stone, in contrast to the case of compressive strength of concrete. The large majority of concretes made with such crushed stone has larger modulus of elasticity than that of mortar.

Figure 13 shows the relation between static modulus of elasticity of crushed stone and concrete.

It is obvious that the larger the modulus of elasticity of crushed stone is, the larger is that of concrete. This tendency differs considerably from that in the

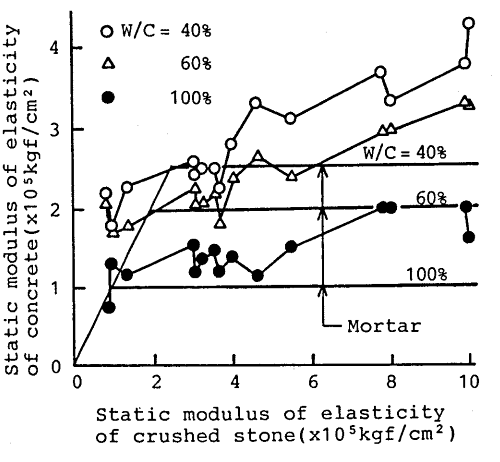

Fig.13 Relation between static modulus of elasticity of crushed stone and concrete

case of compressive strength shown in Fig.5. The difference means that compressive strength of concrete is basically determined by lower quality material, whether mortar or coarse aggregate, and that modulus of elasticity of concrete depends on the average quality of both materials.

Hashin and Hansen [1] derived the following composite equation for modulus of elasticity of concrete.

$$E_c = E_m \frac{(1-V_a)E_m + (1+V_a)E_a}{(1+V_a)E_m + (1-V_a)E_a} \qquad (6)$$

The calculated values from this equation approximately agree with the measured values, including concretes made with low quality crushed stone, as is shown in Fig.14.

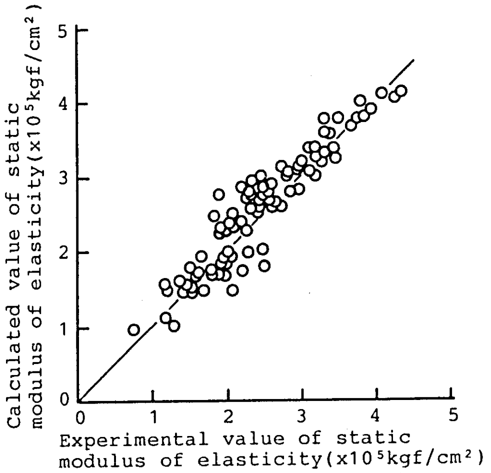

Fig.14 Examination of composite equation on static modulus of elasticity

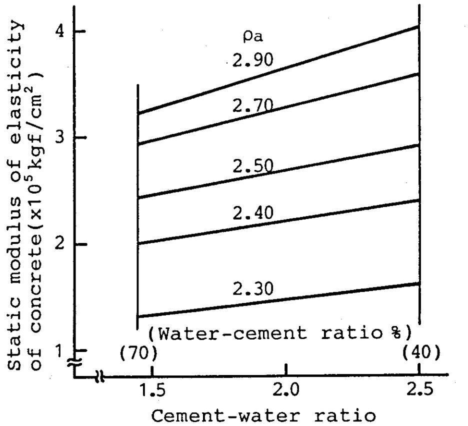

Fig.15 Estimation of static modulus of elasticity of concrete

This equation can be generalized by the same procedure used in the case of compressive strength of concrete. Figure 15 shows the relation among cement-water ratio, static modulus of elasticity of concrete and specific gravity of crushed stone, obtained by the generalized equation.

The modulus of elasticity of concrete made with low quality crushed stone is obviously small. This figure suggests, for example, that it is very difficult to obtain static modulus of elasticity of $2.5 \times 10^5 kgf/cm^2$ in case of using crushed stone having specific gravity below 2.40, even if very small water-cement ratio is chosen.

It is said in general that there is an adequate correlation between modulus of elasticity and compressive strength of concrete. The Standard Specification by JSCE also recognizes the method to estimate modulus of elasticity from the tested value of compressive strength. Figure 16 shows the relation between compressive strength and static modulus of elasticity of concrete, involving the estimated values indicated in the Standard Specification.

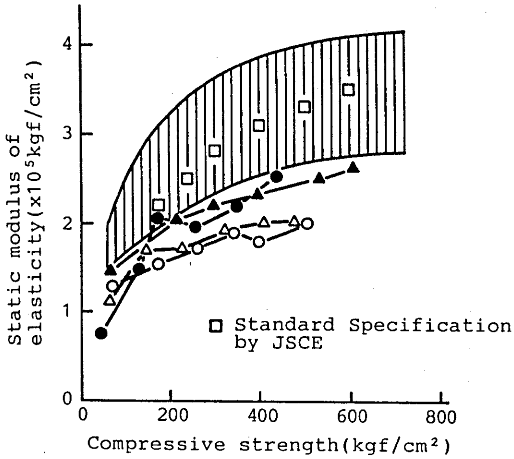

Fig.16 Relation between compressive strength and static modulus of elasticity of concrete

The estimated values look reasonable seemingly because they are plotted on almost the center of the extent of concrete made with crushed stone having adequate quality. However, the extent of the concrete is very wide so that there is a possibility, depending on circumstances, for an actual elastic modulus to be underestimated or overestimated by the values determined by compressive strength. Furthermore, moduli of elasticity of concretes made with low quality crushed stone deviate from the extent, and they are considerably smaller than moduli of elasticity estimated from compressive strength. This means that actual elastic deformation of concrete structure would be larger than the designed value if elastic modulus of concrete made with low quality crushed stone is estimated by the method of the Standard Specification. It is necessary, therefore, to use a measured value of elastic modulus, especially in the case of using low quality aggregate.

3.5 Drying Shrinkage of Concrete

Drying shrinkage of concrete made with crushed stone No.2, 9, 13 and 14 shown in Table 1 was measured. On the assumption that the curve of change in measured shrinkage with passage of time is hyperbolic, the final value of shrinkage was calculated, and used for analysis.

It is well known that drying shrinkage of concrete strongly depends on water content per unit volume of concrete. However, water content is a determining factor of workability of fresh concrete so that it is generally selected considering mainly not drying shrinkage but workability. In this experiment, water content of each mix proportion was selected to be constant, as is shown in Table 2, in order to obtain almost same workability. Therefore, a different conclusion from this experiment would be derived when water content is selected taking a serious view of drying shrinkage instead of workability.

Figure 17 shows drying shrinkage of concrete measured under these experimental conditions. Drying shrinkage of concrete strongly depends upon the quality of aggregate and drying shrinkage of concrete made with low quality crushed stone

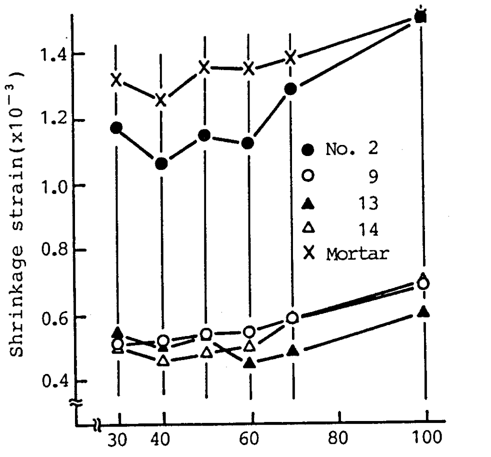

Fig.17 Drying shrinkage of concrete

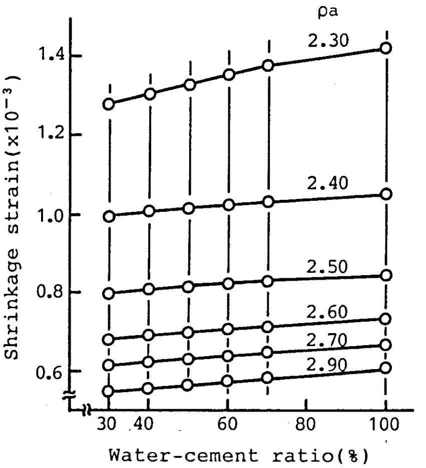

Fig.18 Estimation of drying shrinkage of concrete

is large. Various equations have been proposed to relate shrinkge of concrete to properties of concrete components. Among these equations, the following equations derived theoretically by Hansen and Nielsen [2] seem to be most reliable.

$$\varepsilon_c = \frac{(\varepsilon_m-\varepsilon_a)\{n+1-(n-1)V_a{}^2-2nV_a\}}{n+1} + \varepsilon_a \qquad \text{for } n \geqq E_a/E_m \qquad (7)$$

$$\varepsilon_c = \frac{(\varepsilon_m-\varepsilon_a)\{n+1-(n-1)V_a\}}{\{n+1+(n-1)V_a\}} + \varepsilon_a \qquad \text{for } n \leqq E_a/E_m \qquad (8)$$

ε_c: drying shrinkage of concrete ($\times 10^{-6}$)
ε_m: drying shrinkage of mortar ($\times 10^{-6}$)
ε_a: drying shrinkage of coarse aggregate ($\times 10^{-6}$)

The following equations of drying shrinkage of constituent materials were obtained by experimental results.

$$\varepsilon_m = 3.04W/C + 1179 \qquad (9)$$
$$\varepsilon_a = 1.94\times 10^8 \rho_a{}^{-14.3} \qquad (10)$$

Substituting these equations into the composite equations, drying shrinkage of concrete can be expressed by more general factors. Figure 18 shows the shrinkage obtained by the generalized equations.

Because elastic modulus of low quality crushed stone is small, its ability to restrain shrinkage of mortar is poor. This is one of the reason of large shrinkage of concrete made with low quality crushed stone. Another reason is relatively large drying shrinkage of crushed stone itself which has been considered to be negligible.

It is recognized from this figure that the less the water-cement ratio is, the less is the drying shrinkage of concrete. However, the effect of water- cement ratio on drying shrinkage of concrete is smaller than that of quality of aggregate. It is very difficult to decrease drying shrinkage of concrete by adjusting mix proportion under the condition that water content is fixed.

3.6 Frost Resistance of Concrete

The result of freezing and thawing test is shown in Fig.19. Although the data are not sufficient, it is obvious that the quality of crushed stone strongly affects on the frost resistance of concrete. In the case of water-cement ratio of 70%, the smaller the absorption of coarse aggregate is, the smaller is the decrease in relative dynamic modulus of elasticity of concrete due to freezing and thawing. However, a certain degree of the decrease is inevitable even if high quality crushed stone is used, because of poor frost resistance of mortar. It is very important to increase the frost resistance of mortar regardless of the quality of coarse aggregate.

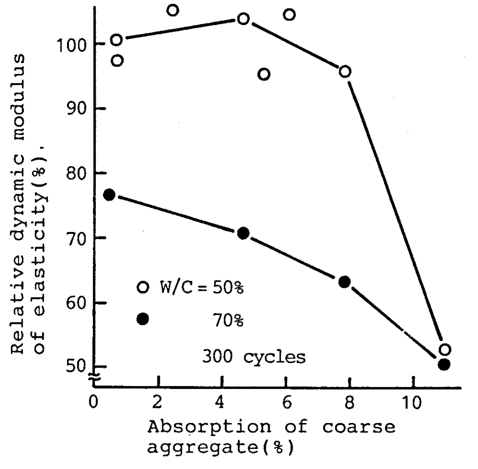

Fig.19 Frost resistance of concrete

In the case of water-cement ratio of 50%, the frost resistance of mortar seems to be satisfactory. In fact, there are some examples that concrete did not deteriorate even though low quality crushed stone having comparatively large absorption was used. This means that such mortar makes up for the defect of using low quality aggregate. However, a proper frost resistance of concrete made with extremely low quality crushed stone would be hardly expected even if such mortar is used. The frost resistance of concrete is thought to be basically determined by lower quality material, whether mortar or coarse aggregate, in the same manner as compressive strength. Deterioration of low quality aggregate itself can cause frost damage of concrete, so it seems impossible to use extremely low quality aggregate in a cold region.

4. POSSIBILITY OF EFFECTIVE USE OF LOW QUALITY AGGREGATE BY MIXING WITH GOOD QUALITY AGGREGATE

4.1 Strength of Concrete

It was examined whether low quality aggregate can be effectively used by mixing with good quality aggregate. Two combinations of mixing aggregate were chosen from Table 1. One is the combination of extremely low quality crushed stone No.1(A) and very high quality crushed stone No.15(D). In another combination, crushed stone No.4(B) and No.10(C), whose difference in quality is comparatively small, were mixed. These mixed aggregate will be called as crushed stone A-D and crushed stone B-C respectively in the following examination. Percentage of good quality crushed stone to total volume of coarse aggregate was varied, such as 0% (low quality crushed stone only), 20%, 40%, 60%, 80% and 100% (good quality crushed stone only). Three kinds of mix proportion from Table 2, water-cement ratio of 30%, 50% and 70%, were used.

Figure 20 shows compressive strength of concrete. The horizontal axis in the figure indicates the percentage of good quality crushed stone.

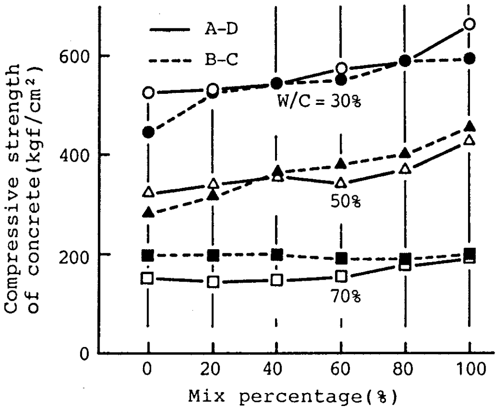

Fig.20 Compressive strength of concrete

In the cases of water-cement ratio of 30% and 50%, the mixing of coarse aggregate seems to be effective because the larger the percentage of good quality crushed stone is, the larger is the compressive strength of concrete. On the other hand, compressive strength in the case of water-cement ratio of 70% is not increased with percentage of good quality crushed stone, especially when crushed stone B-C is used.

Compressive strength of concrete is basically determined by lower quality material, whether mortar or coarse aggregate, as described before. In the case of that increase in strength of concrete is tried by using mixed aggregate, the strength cannot also surpass that of mortar, even if extremely high quality aggregate is mixed. If water-cement ratio is very large, strength of mortar would be less than that of aggregate. The increase in strength of concrete by using mixed aggregate could not be expected under this condition, because strength of concrete is determined by that of mortar. The case of water-cement ratio of 70% in the figure seems to correspond to this condition.

The effect of using mixed aggregate on properties of concrete is illustrated schematically in Fig.21. It goes without saying that the effect of using mixed aggregate is ideal in case of type (a) in the figure, but is not well for type (c).

In order to compare experimental result with this figure, Fig.20 was rewritten as shown in Fig.22. Compressive strength is expressed here in values relative to the strength of concrete made only with low quality crushed stone (mix percentage: 0%). The case of water-cement ratio of 70% was omitted because of

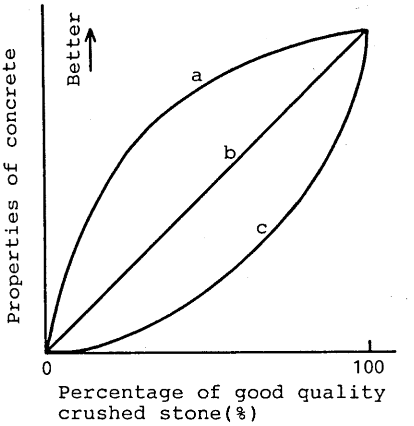

Fig.21 Effect of using mix aggregate on properties of concrete

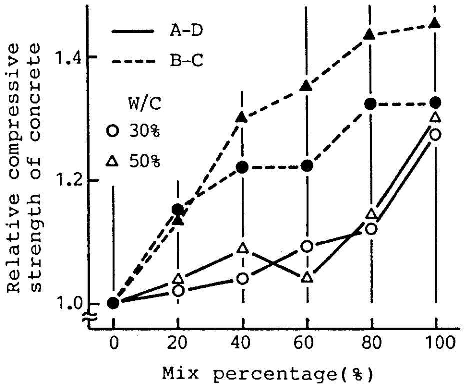

Fig.22 Relative compressive strength of concrete

the less effect of using mixed aggregate.

The effect of mixing aggregate obviously depends on the combination of crushed stone. Crushed stone B-C is close to the ideal type (a), but crushed stone A-D which does not show clear effect under mix percentage of 60% is similar to the type (c). It is necessary therefore to use mixed aggregate after thoroughly examining the type of the aggregate.

According to Fig.1, the quality of particles in crushed stone does not vary widely compared with that in gravel, but large number of particles of extremely inferior quality are included in low quality crushed stone such as A. These particles within concrete can be defect of concrete strength, so that particles of extremely inferior quality in mixed aggregate would prevent increase in strength of concrete even if percentage of good quality aggregate is increased. The insufficient improvement in strength of concrete made with crushed stone A-D seems to be caused by these particles of extremely inferior quality. This means that it is necessary to examine the uniformity of particles also in the case of using mixed aggregate.

Figure 23 shows tensile strength of concrete, expressed in values relative to the strength of concrete made only with low quality crushed stone.

The improvement in strength by mixing of aggregate is not remarkable in all cases, corresponding to the type (c) in Fig.21. Furthermore, the strength is decreased by using mixed aggregate in the range of mix percentage of 20% to 60% in the case of crushed stone A-D. Using mixed aggregate which brings about decrease in the strength obviously results in a reverse effect. Although the cause of the decrease is not clear, it is presumed that deviate of strength distribution within concrete, caused by the combination of crushed stones having extremely different quality with each other, has a bad influence upon the tensile strength.

4.2 Elastic Properties of Concrete

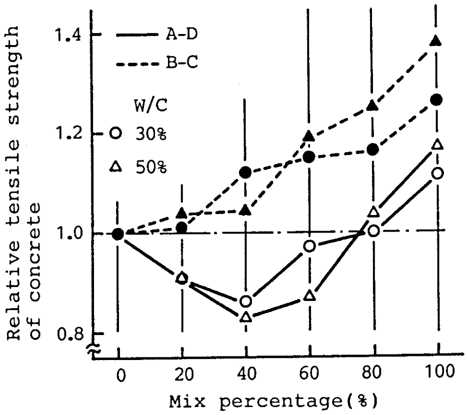

Fig.23 Relative tensile strength of concrete

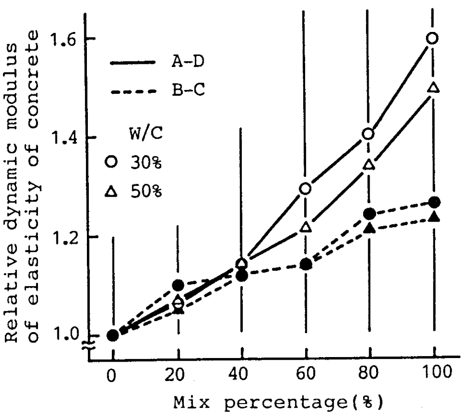

Fig.24 Relarive dynamic modulus of elasticity of concrete

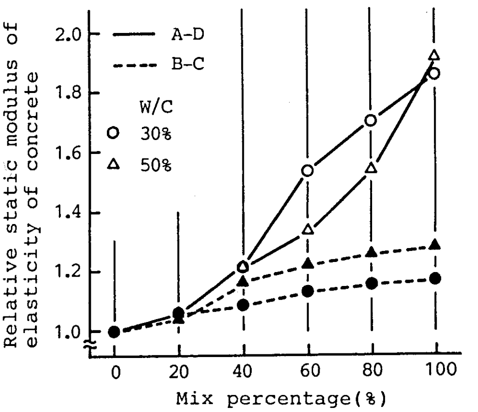

Fig.25 Relative static modulus of elasticity of concrete

Figure 24 and 25 show relative dynamic and static modulus of elasticity of concrete respectively.

The mixing of aggregate is effective because moduli of elasticity increase almost linearly with the percentage of good quality crushed stone in all cases. This means that modulus of elasticity of concrete depends on the average quality of mixed aggregate. On the assumption that good quality crushed stone is mixed with matrix composed of mortar and low quality curushed stone, static modulus of elasticity of concrete made with crushed stone A-D was calculated according to equation (6). Figure 26 shows the result.

The culculated values approximately agree with the experimental values, so improvement of elastic modulus due to mixing good quality aggregate can be estimated by the composite theory.

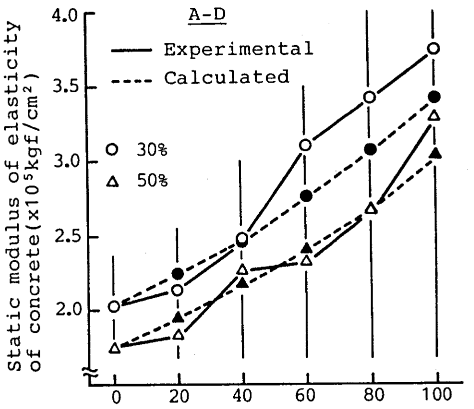

Fig.26 Examination of composite equation on static modulus of elasticity of concrete

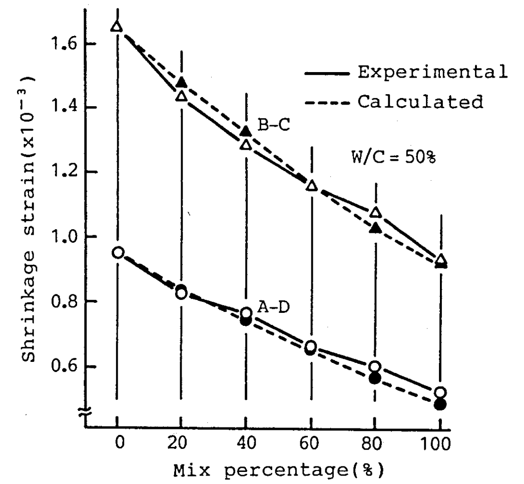

Fig.27 Drying shrinkage of concrete

4.3 Drying Shrinkage of Concrete

Figure 27 shows the final value of drying shrinkage of concrete made with mixed aggregate.

Because drying shrinkage decreases almost linearly with increase in the percentage of good quality crushed stone, shrinkage seems to depend on the average quality of mixed aggregate in the same manner as modulus of elasticity. The values of shrinkage calculated from composite equation (7) and (8) on the same assumption as in the case of elastic modulus are shown in the figure. The culculated values agree well with the experimetal values, so the improvement of drying shrikage can be also estimated by the composite theory.

4.4 Frost Resistance of Concrete

The result of freezing and thawing test in the case of water-cement ratio of 50% is shown in Fig.28. Because concrete made with crushed stone B-C did not practically deteriorate, only the result of concrete made with A-D is indicated in the figure.

Although improvement of frost resistance due to mixing aggregate corresponds to the ideal type (a) in Fig.21 up to freezing and thawing cycles of the order of 200, it shifts gradually to the type (c) with increase in the cycle. It is strongly feared that low quality aggregate harms frost resistance of concrete, even if good quality aggregate is mixed.

In the case of water-cement ratio of 70%, the larger the percentage of good quality aggregate is, the less is the deterioration of concrete. However, frost resistance of concrete using this water-cement ratio is not sufficient on the whole because of poor resistance of mortar. It is very important to increase the frost resistance of mortar by adjusting mix proportion also in the case of

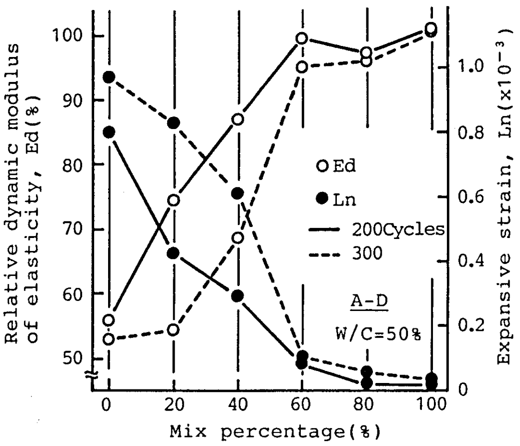

Fig.28 Frost resistance of concrete using mixed aggregate.

5. CONCLUSION

In this experiment, it was examined whether low quality aggregate can be effectively used by methods of ajusting mix proportion and mixing good quality aggregate. Although the problem of low quality aggregate is not solved completely by these methods, there seems to be the possibility of using the low quality aggregate by properly adapting these methods according to the required properties of concrete.

The followings were learned within the scope of this investigation.

(1) A certain high strength of concrete can be obtained by selecting proper mix proportion, even if low quality aggregate is used. Strength of concrete is also increased, to some degree, by mixing good quality aggregate in many cases, but it is decreased according to the combination of aggregate. It is necessary to use mixed aggregate after thoroughly examining the effect of mixing.

(2) Elastic properties of concrete is strongly influenced by the quality of aggregate, so that there is a limit in improvement of elastic properties even if mix proportion is adjusted. On the other hand, an effect in proportion to mixing can be expected in the case of using mixed aggregate.

(3) Using mixed aggregate seems to be larger than that of adjusting mix proportion also in the case of drying shrinkage of concrete.

(4) Frost resistance of concrete is thought to be basically determined by lower quality material, whether mortar or coarse aggregate, in the same manner as compressive strength, so that neither adjusting mix proportion nor using mixed aggregate seems to be a usuful method. However, a certain degree of frost resistance would be obtained by proper combination of both methods unless used aggregate is extremely low quality.

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