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EFFECT OF ABRASION ON DOWNSTREAM GRAVEL-SIZE REDUCTION IN THE WATARASE RIVER, JAPAN: FIELD WORK AND LABORATORY EXPERIMENT*

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ABSTRACT

Two processes have been considered to explain downstream grain-size reduction in gravel-bed rivers. One is sorting which results in finer grains being transported downstream faster and further than the larger ones. The other is abrasion by which individual particles are diminished in size.

Previous experimental studies on abrasion of gravels showed much lower diminution rates than those of gravels in natural rivers. Therefore most studies on the cause of downstream fining in rivers stress the downstream reduction of grain size by sorting. However, broken boulders are often observed among river-bed materials in Japan and sometimes grain-size changes have a great deal to do with the difference in resistance to breakdown among lithologies. The purpose of this study is to examine the effect of abrasion on downstream fining in the field and then compare this effect with laboratory results to determine if abrasion is responsible for longitudinal changes in gravel size.

The lower part of the Watarase River in eastern Japan was selected for the study reach. In the lower reach, the Watarase River flows on a dissected alluvial fan, which means that the river is no longer aggrading. In addition, the study reach is only slightly influenced by the input of gravel from tributaries. Bed gravel in the study reach consists of several different lithologies; andesite, quartz-porphyry, sandstone, hornfels, and chert. The grain size distribution and the lithologic compositions of the river-bed material were examined at nine sites.

There are two principal results from these analyses. **i)** Size distribution of gravel is strongly related to lithologic composition. Andesite boulders or large cobbles make up the framework sizes in the upstream part, while chert pebbles make up the framework sizes in the downstream part of the study reach. There are few andesite pebbles or chert boulders in the river-bed. **ii)** Longitudinal changes in the composition of each grain size class show that selective transport by lithology occurrs in every gravel size. Since the mobility of gravel depends mainly on its size, hydraulic sorting by lithology does not occur within the same size class. These results clearly indicate that particle abrasion does occur in the Watarase River and is responsible, at least in part, for the downstream decrease in particle size of bed material.

Previous experimental studies on abrasion do not replicate well the grain-to-grain impact between bedload gravels and bed gravels in a natural river during large floods. This study used a rotating drum with three vanes inside, called the "ERC abrasion mixer", as an experimental

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apparatus to produce repeated collisions among test gravel particles and to simulate closely the impact velocity of collision (3m/sec at maximum) occurring in the Watarase River during a flood. Test gravels of slightly weathered andesite and chert were obtained from the bed of the Watarase. Uniform materials of three sizes (L: $-7.0\phi \sim -6.5\phi$, M: $-5.5\phi \sim -5.0\phi$, S: $-4.0\phi \sim -3.5\phi$) and mixtures of two of the three sizes were used to evaluate abrasion properties under vigorous impact conditions.

There are five principal results from the experiment. **i)** Test gravels breake frequently and decrease in weight rapidly. **ii)** Abrasion of chert produces mostly gravel while andesite produces mostly sand and silt. **iii)** L-size chert cobbles decrease in weight rapidly as a result of being broken into smaller pieces, while andesite cobbles breake so rarely that their weight decreases very slowly. **iv)** S-size andesite pebbles decrease in weight more rapidly than chert. **v)** Size mixture affects abrasion strongly, with smaller fragments being crushed by the larger gravel particles.

Lithologic grain-size reduction and some characteristics of lithologic composition of the river-bed material in the Watarase River can be explained by the results of the ERC abrasion mixer experiment. Diminution coefficients of andesite and chert obtained from the ERC abrasion mixer experiment are in the range of $10^{-3} \sim 10^{-1}$ km^{-1}. These are larger by one to two orders of magnitude than those from previous experiments on abrasion. This results mainly because the ERC abrasion mixer experiment closely simulates particle to particle collisions during floods in the Watarase River. In addition, diminution coefficients from the ERC abrasion mixer experiment are consistent with those obtained from many Japanese rivers on alluvial fans ($10^{-2} \sim 10^{-1}$ km^{-1}). This result shows that a downstream reduction of size of river-bed gravels can be explained by abrasion alone.

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CHAPTER I

INTRODUCTION

It is commonly observed that grain size in a gravel-bed river decreases in the downstream direction. It has been surmised that this downstream grain size reduction is due to some combination of the following two factors (e.g., Pettijohn, 1957; Knighton, 1984; Kukal, 1990; Mangelsdorf *et al.*, 1990; Parker, 1991a, 1991b): **i)** abrasion, through which individual particles are diminished in size; and **ii)** sorting, by which finer grains are preferentially transported downstream faster and further than the larger ones (differential transport), or in which only the fraction of the bed material smaller than a threshold size is transported by a given flow event (selective entrainment, selective transport). In the usage of the term "abrasion", this study will follow Kuenen (1956) to include all mechanisms of wear such as splitting, crushing, chipping, superficial cracking, grinding and sandblasting, etc.

It may make a great difference in long-term sediment budgets and fluvial geomorphology whether or not abrasion is more important than sorting. For example, we can see a great difference in the interpretation of the behavior of maximum-size particles. That is, from the abrasion point of view, the largest particles can be transported during a huge flood and be abraded gradually. On the other hand, from the sorting point of view, maximum gravels are regarded as those which can be barely transported in the downstream direction over long time intervals. These different interpretations make it difficult to analyze the sediment budget in a drainage area. Therefore it is very important to to evaluate the relative influence of these factors on longitudinal grain-size distribution.

1.1 Field evidence to suggest the significance of abrasion on downstream fining

The author's research on alluvial fans in many Japanese rivers in temperate humid climates indicates that abrasion plays an important role in the downstream fining of gravel.

Broken particles are commonly observed among river-bed gravel in Japan (**fig. 1.1**). About 20 to 30% of the river-bed gravel show the "broken round" shape (**fig. 1.2;** Brentz, 1929a, 1929b) in the Azusa River, Matsumoto Basin, central Japan and in the Sagae River, Yamagata Basin, north-eastern

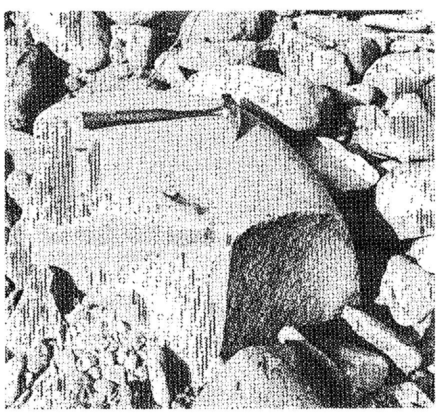


Fig. 1.1 A broken boulder on a river-bed. This photo was taken at the Azusa River, Matsumoto basin, central Japan.

Japan (Kodama, 1990b; see **appendix I**). During a large flood, a sound like thunder with earth tremor can be heard from the bank, particularly in rivers with large boulder beds. This sound might be generated by collisions between transported and stationary gravel in the bed. Percussion marks (**fig. 1.3;** e.g. Gilbert, 1905; Wentworth, 1919; Campbell, 1963; Lamb and Johnson, 1963; Oya, 1981; Johnson *et al.*, 1989) on the surface of particles are evidence of these collisions. For instance, percussion marks with a diameter of 5 to 6mm, which are often observed on the surface of chert gravel, are inferred, according to the equation proposed by Oya (1981), to be formed by the collision of cobbles about 10cm in diameter at velocities of 2 to 3m/sec. Thus gravel particles collide violently during flood and may be

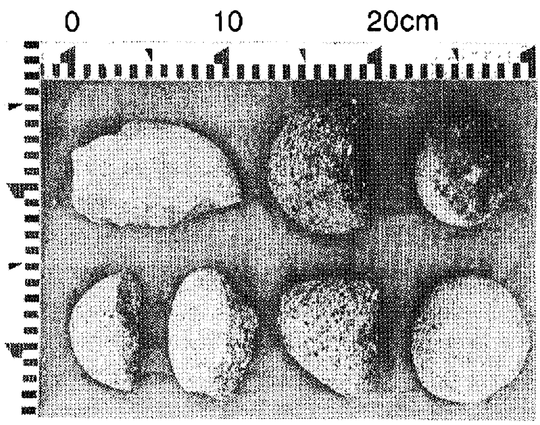


Fig.1.2 Various shapes of andesite cobbles. The left three cobbles are called "broken round" contrasting with the right two "rounded" cobbles. The center two cobbles are called "transition" (after Kodama, 1990b). It is apparent that broken rounded cobbles are split. Transition gravel particles are regarded as once split and subsequently rounded.

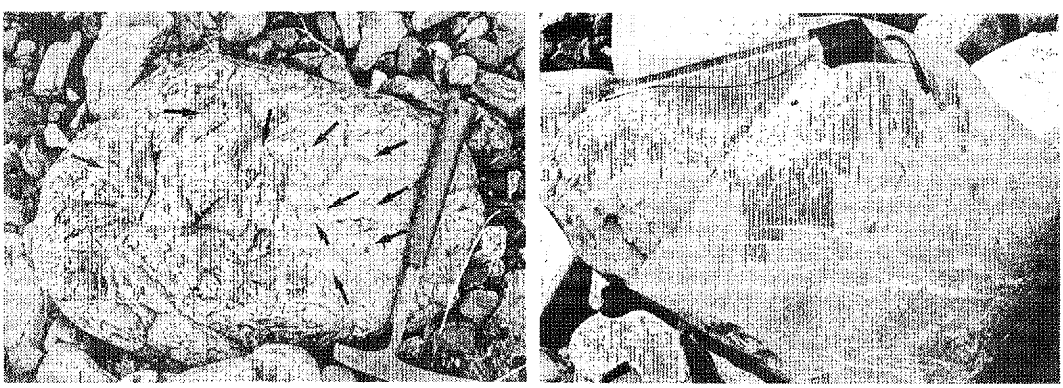


Fig.1.3 Percussion marks on the surface of a boulder on a river-bed.
Left photo: Crescentic gouges indicated by arrows are called "percussion mark", which indicate particle to particle collisions during floods.
Right: White scratches on a hornfels boulder show impact by other particles transported at high water stages. Flow was from right to left.
Left photo was taken at the Ohi River (central Japan), and right photo was taken at the Azusa River (central Japan).

broken down easily.

Some gravel particles are strongly asymmetric (**figs. 1.4 and 1.5**). On the upstream side, where other gravel particles collide, surface textures are usually rough, and there are many tiny grooves or notches along bedding or joints. On the downstream side, which is scooped out as with a spoon, surface textures are smooth (**fig. 1.4**). Small particles in eddies generated on the lee side of the gravel seem to polish the surface during floods. A large gravel particle can become smaller *in situ* by collisions from other large particles or by abrasion by small particles.

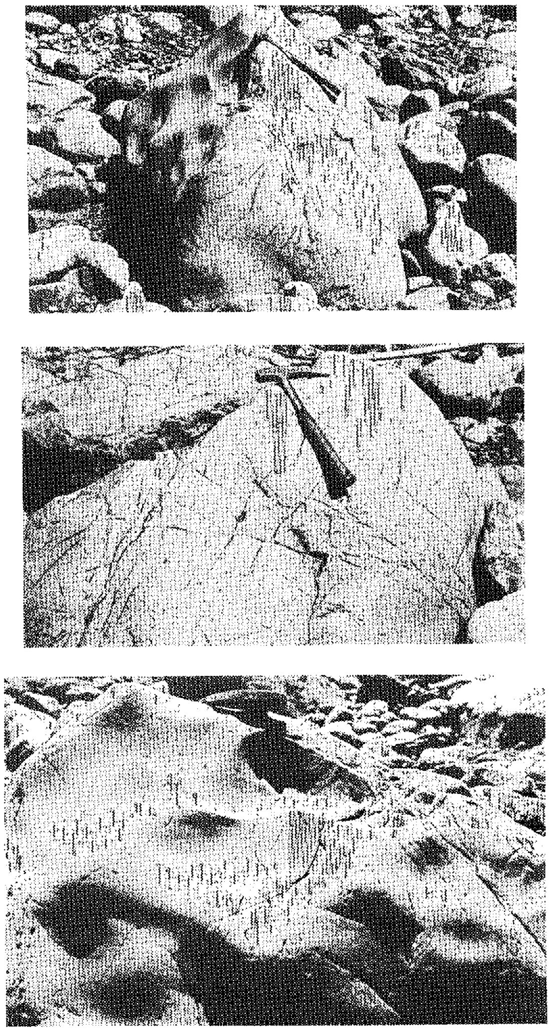


Fig. 1.4 A asymmetric shaped boulder (sandstone in the Ohi River).
Top photo: Right side of this picture is upstream. A boulder in the center is a symmetric shaped boulder.
Middle: This photo was taken from the upstream side of the boulder of the top photo.
Bottom: This photo was taken from the downstream side of the boulder of the top photo.

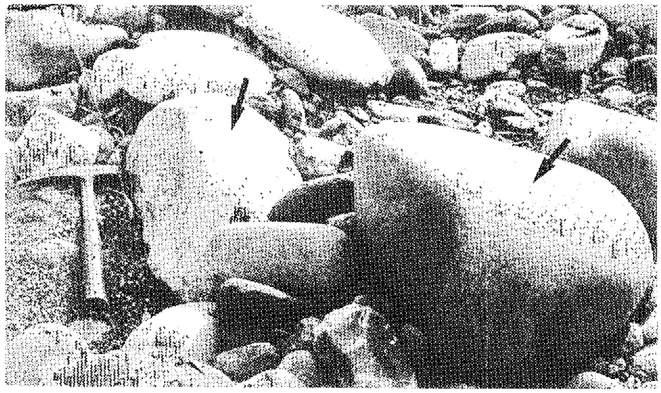


Fig.1.5 Asymmetric shaped boulders. Flow is from right to left. There are two asymmetric boulders indicated by arrows. Downstream faced surface of the boulder on the left side, granite, is rough as the result of splitting. On the other hand, the downstream faced surface of the boulder on the right side, andesite, shows scooped out shape. The author thinks that the shape of the boulder on the left side is in preparatory stage relative to the boulder on the right side. Rough surface would be polished by fine particles in the segregated eddies generated under the lee side of the broken rounded particles during floods.

Limestone, mudstone, slate, and granite gravels often decrease in proportion to other lithologies among bed gravel in the downstream direction. This decrease might be caused by lower resistance to abrasion of these lithologies. (Ikeda, 1970; Kodama, 1988).

Artificial blocks used for the protection of banks and beds have been transported to the center of the channel in many rivers (**fig. 1.6**). Sometimes these blocks have diameters more than twice those of the largest natural bed particles. This indicates the possibility that rivers have competence to transport particles larger than the maximum size found on their bed. In addition, recent studies on the transport of mixtures (e.g. Meland and Norrman, 1969; Ikeda and Iseya, 1987; Iseya and Ikeda, 1987) suggest that larger gravels are easier to move by flow, which is contrary to the basic idea to support downstream fining by sorting.

1.2 Previous studies on downstream fining

Studies which emphasize the importance of abrasion on grain-size distributions have been few in number (e.g. Sneed and Folk, 1958; Ikeda, 1970, 1985; Adams, 1979; Ibbeken, 1983; McBride and Picard, 1987). Many of them stress differences in resistance to breakdown within lithologies. On the other hand, recent studies stress the downstream reduction of grain size by sorting (e.g. Knighton, 1980, 1982; Brierley and Hickin, 1985; Shih and Komar, 1990a, 1990b; Komar and Carling, 1991). This tendency to emphasize selective transport, as opposed to abrasion seems to depend on the following two results.

i) Previous experimental studies on abrasion of gravels show much lower diminution rates than those of gravels in natural rivers (e.g. Kuenen, 1956). **ii)** Three field studies which evaluat the relative importance between abrasion and sorting (Plumley, 1948; Bradley *et al.*, 1972; Dawson, 1988) also show that abrasion has much less effect than sorting on downstream fining in rivers.

Referring to the first result, most experiments on abrasion of gravel employed tumbling mills or circular flumes (e.g. Daubrée, 1879; Wentworth, 1919; Marshall, 1927, 1929; Krumbein, 1941a; Rayleigh, 1942, 1944; Sarmiento, 1945; Potter, 1955; Kuenen, 1955, 1956; Bradley, 1970, Bradley *et al.*, 1972; Watanabe, 1973; Moriwaki *et al.*, 1985; Kodama, 1990a). Diminution coefficients so obtained cannot fully explain the amount of downstream fining occurring in natural rivers (Shaw and Kellerhals, 1982, fig. 17 and table 12). Kuenen (1956) concluded that abrasion is a minor factor in downstream fining.

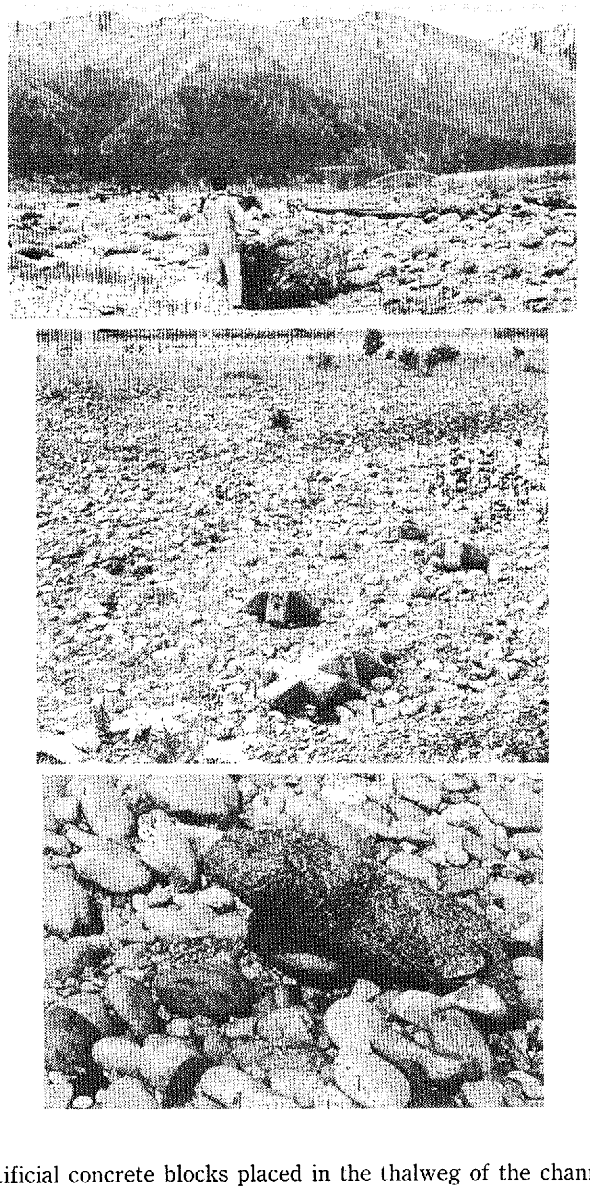


Fig.1.6 Artificial concrete blocks placed in the thalweg of the channel.
Top photo: Upstream view at the Kurobe River (central Japan).
Middle: The Azusa River (central Japan). Left side is upstream.
Bottom: This concrete block (the largest) was well abraded and has rounded corners. This photo was taken downstream from the middle one.

Shaw and Kellerhals (1982) pointed out that "two further processes may be responsible for the remaining, unexplained, abrasion. First, vibration of particles occurs with streamflows slightly below those flows necessary for the initiation of particle motion (Schumm and Stevens, 1973). Second, pot-holing and rounding of bedrock exposed in stream beds shows that coarse material at rest is abraded by collisions with particles in transport."

Regarding the second result, Plumley (1948, p.570) concluded from a longitudinal change in lithologic composition of gravel (-4.0ϕ to -5.0ϕ) from terrace deposits that "selective transport accounts for 75 per cent of the size reduction observed in Rapid Creek and abrasion for the remaining 25 per cent". Bradley *et al.* (1972) concluded from a comparison of reduction in gravel size along 16 miles of the Knik River with size reduction of Knik River gravel in a circular flume experiment that "sorting processes are responsible for 90 to 95 percent of the reduction in size of Knik River gravel, with the balance being attributable to abrasion". Dawson (1988) compared the diminution rate obtained from rivers known to be aggrading with that from degrading rivers and concluded that grain size diminution is predominantly accounted for by differential transport. Arguments against these three previous studies will be presented in **chapter 4.3.**

Conclusions that abrasion is a minor factor in downstream grain size diminution have recently won broad support. This might be why most studies on the causes of downstream fining in rivers pay much attention to sorting processes.

There have been many varieties of studies on sorting processes. For instance, studies on the correlation between distributions of grain size and channel gradients (Blissenbach, 1952), on relations to the shape of gravels (Lane and Carlson, 1954; Bluck, 1965), on the reduction in grain size from models of sediment transport (e.g. Rana *et al.*, 1973; Deigaard and Fredsøe, 1978), on gravel supplies from tributaries and selective transport from them (Knighton, 1980, 1982; Ichim and Radoane, 1990), on the relation with channel patterns (Brierley and Hickin, 1985), on the shear stress with mixed size materials (e.g. Komar, 1987; Komar *et al.*, 1989), and on the correlation between hydraulics and the sample size distributions of tractive sediments in actual rivers (Ashworth and Ferguson, 1989; Shih and Komar, 1990a, 1990b).

There are also many studies which relate abrasion and differential transport to whether the river is actively degrading or aggrading (Russell, 1939; Mackin, 1948; Bradley *et al.*, 1972; Shaw and Kellerhals, 1982; Dawson, 1988). That is, in a degrading system, abrasion processes dominate and in an aggrading system, sorting processes dominate. In addition, in a drainage system which is undergoing tectonic subsidence, sorting is the dominant process (Paola, 1988). If a stream is aggrading or the sediment is trapped by subsidence, then coarse particles, which may have few chances to be moved, will be progressively buried before "catching up" with the fine particles, which are moved over a wide range in stage (Allen, 1965). Accordingly, grain size will fine downstream more rapidly in an aggrading system than in a degrading system. Therefore, a description of the vertical movements of the stream must be involved in any explanation of the observed pattern of grain size distribution in a river (Shaw and Kellerhals, 1982).

1.3 Purpose of this study

According to the observations stated in **chapter 1.1**, abrasion seems to be the main process that accounts for downstream fining in river-bed materials. The purpose of this study is to examine the effect of abrasion on downstream fining in the field and compare it with laboratory results to determine if abrasion is responsible for longitudinal changes in gravel size.

Many rivers in Japan have dissected alluvial fans and formed terraces (Saito, 1988). This means degradation has occurred over time periods on the order of 10^4 years. Furthermore, gravel and sand of alluvial fans in Japan are not the original glacial deposits. They are regarded as sediments transported mainly by fluvial processes. Gravel size decreases downstream at a rapid rate of half the diameter in about 10km.

The Watarase River, central Japan, was chosen as a study area, because it has a variety of gravel lithologies which may have different abrasion properties. In addition the lower part of the Watarase is influenced little by gravel input from tributaries, and river-bed materials are transported annually.

CHAPTER II

River-bed sediment of the lower Watarase

2.1 Study area

2.1.1 General description

The Watarase River in eastern Japan originates at Ashio, flows between Mt. Akagi (volcano) and Ashio Mountain to the south-west, changes its direction to the south-east at Ohmama, flows through Kiryu, Ashikaga, and flows into the Tone river at Koga. The Watarase River is about 108km long and the area of its drainage basin upstream of Fujioka is about 1,210km^2 (**figs. 2.1 and 2.2**).

Floods usually occur in summer and autumn and are caused by typhoons or stationary fronts. Discharge at Ashikaga hydrometric gauging station is commonly several 100m^3/sec a few times per year and about 1,000~2,500m^3/sec during floods of recurrence intervals of a few years. In 1947 Typhoon Catherine produced a flood discharge of 4,700m^3/sec and Typhoon No.26 in 1966 produced one of 4,100 m^3/sec (data from the Watarase River Work Office, Kanto Regional Construction Bureau, the Ministry of Construction).

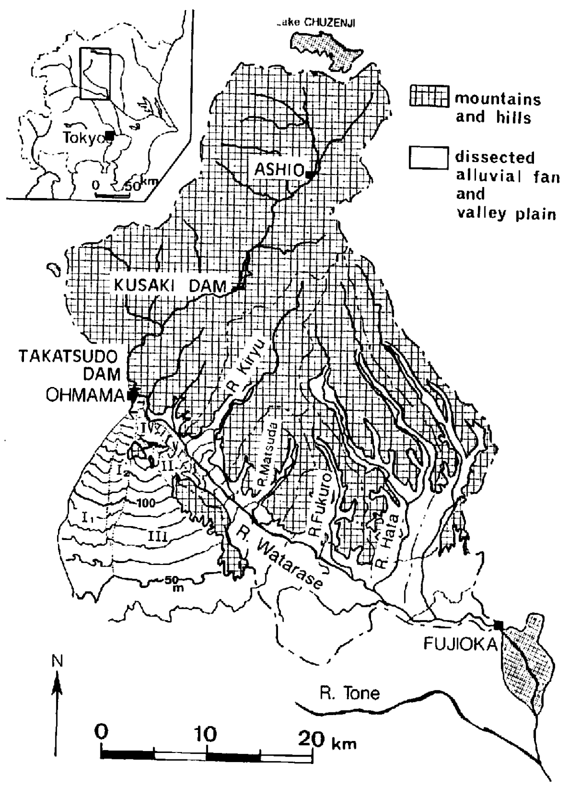


Fig.2.1 The drainage area of the Watarase River (Upper of Fujioka) and Ohmama alluvial fan. Contour interval on the alluvial fan is 10m. Terrace plains divided by dotted lines on the alluvial fan are numbered from I to V respectively.

The Watarase River built the Ohmama alluvial fan, which has a diameter of about 18km (**fig. 2.1**). The Watarase River has dissected this fan (Machida, 1951, 1963) and formed a trench which is about 30~40m deep and 1.5km wide at the apex. Bedrock exposures in the river-bed and the bank are common near the apex but very rare downstream from Kiryu.

There are two dams along the Watarase River, the Takatsudo dam constructed in 1973 and the Kusaki dam constructed in 1977. The former is small and was almost filled with sediment in 1974. Afterward, the sedimentation level changed little. This means that Takatsudo dam has not affected sediment transport since 1974. In contrast, Kusaki dam is large and traps almost all sediment, mainly sand and silt with little gravel (Ikeda *et al.* 1985). It is not clear, however, whether or not sediment trapped by the Kusaki dam has affected river-bed gravel in the lower part of the Watarase. Since the distance of gravel particles transported by a flood is usually less than several hundred meters and many gravels are trapped inside bars for a long time awaiting reworking (Tada *et al.*, 1952, 1953, 1955, 1957; Tada, 1964, pp.109–116), the effect of this dam on gravel particles in the lower part of the Watarase must be very small.

Figure 2.2 shows the lithology of the mountainous part of the drainage area of the Watarase River. Ashio mountain consists of Permian and Jurassic sedimentary rocks including mainly chert, sandstone and slate (Editorial Committee of KANTO, 1986, p.48–49). In Cretaceous time granite intruded these sedimentary rocks near Sohri and formed a hornfels belt by contact thermal metamorphism (Editorial Committee of KANTO, 1986, p.60). Quaternary andesite is distributed in the western part of the

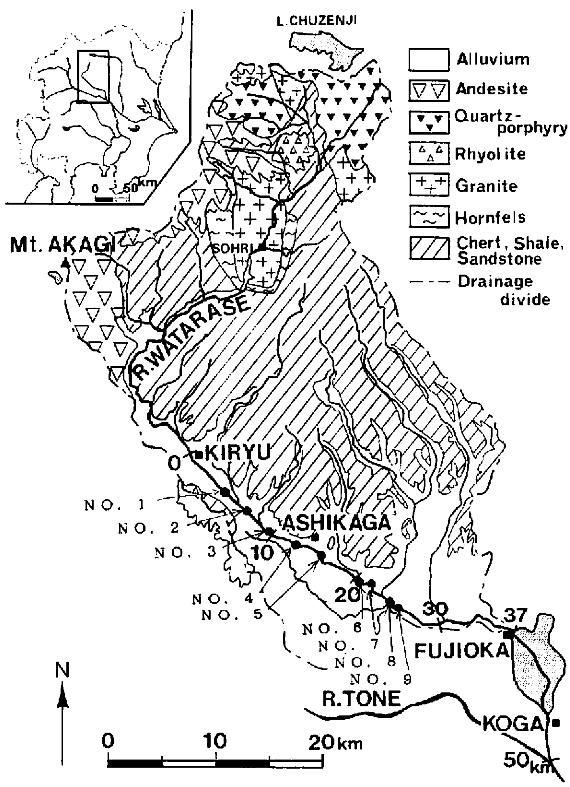


Fig.2.2 Lithology of the mountainous part of the drainage area of the Watarase River and location of the sampling sites.

drainage and quartz-porphyry and rhyolite are in the northern part.

These rock types are found as gravels in the river-bed of the Watarase (Komine, 1954). Both granite and slate gravels, however, decrease rapidly in size downstream (Ikeda, 1985) and are very rare downstream of Kiryu. Rhyolite gravel is also rare in the lower part of the Watarase River because of its scarcity in the drainage area.

2.1.2 Study reach

Downstream distance from Kiryu along the Watarase is shown in **fig. 2.2**. The confluence with the Tone river is 50km downstream of Kiryu and the Kusaki dam is located 28km upstream of Kiryu. In this article, distance downstream from Kiryu will be used to identify the location along the Watarase.

The river-bed slope decreases rapidly (Yatsu, 1954a) near Ashikaga at about 17km (**fig. 2.3**) on the gravel-bed reach. River-bed materials change abruptly from gravel & sand to sand at about 25km (Kodama and Inokuchi, 1986).

An intensive study was carried out over the gravel-bed reach (0 to 25km), where the river width ranges from about 250m (upstream part) to 100m (downstream part) and the length of gravel bars varies from approximately 800m to 300m. This reach is suitable for studying gravel abrasion based on downstream changes of lithologic composition for the following two reasons. First, this reach is regarded as a sediment transport system through which gravels supplied from upstream travel downstream in the course of years. Gravel contamination from tributaries has little effect because tributaries deliver a minor amount of sediment to the Watarase. In other words, this reach might be compared to a flume. Second, judging from the distribution of river terraces in the Ohmama alluvial fan, the bed elevation of the Watarase River has remained fairly stable for the last thousand years. This fact suggests that sediment transport of the Watarase has reached equilibrium.

Several streams draining Ashio mountain join the Watarase in the study reach, the Kiryu (at 6.0km), the Matsuda (at 9.0km), the Fukuro (at 20.4km) and the Hata (at 23.4km) (**fig. 2.1**). Gravel input from

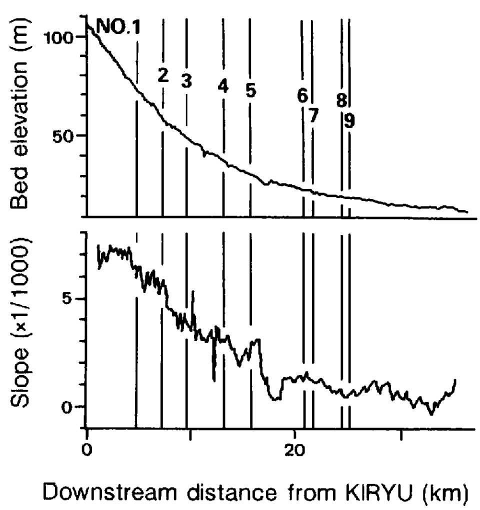


Fig.2.3 Longitudinal profile of the lower part of the Watarase River (top figure, see **appendix II**) and longitudinal change of the river-bed slope (bottom, Mean slope was calculated over a reach of 2 to 2.5km long in order to smooth bar topography).

these streams is minor in quantity compared with the amount of gravels transported by the Watarase. Evidence for this is as follows: first, even the largest tributary, the Hata, transmits 900m^3/sec in designed peak flood discharge (according to the Watarase River Work Office, Kanto Regional Construction Bureau, the Ministry of Construction), while the Watarase transmits from 3,500m^3/sec (at Kiryu) to 4,500m^3/sec (at Fujioka). All other tributaries show less than 20% flood discharge of the Watarase. Second, the Kiryu (700m^3/sec in designed peak flood discharge) transports a small amount of gravel to the Watarase judging from the bed materials of the Kiryu near its confluence with the Watarase. But the confluence of the Kiryu is located at the upstream section of the study reach (at 6.0km). Bed materials of other streams at their confluence with the Watarase consist mainly of sand, silt and clay.

On a 10^4 year time scale, the bed of the Watarase River is degrading. It has dissected the Ohmama alluvial fan and formed several terraces. During the last several thousands years, the Watarase River has maintained a fairly stable bed level, as indicated by the small relative height (several meters) between the flood-plain and a set of Holocene terraces distributed partly along the right bank downstream from Kiryu.

2.2 Downstream changes of the river-bed sediment in the Watarase River

2.2.1 Grain size distributions

i) Sample collection and analysis

Bed material on gravel bar surfaces was sampled at low water stage. The author paid particular attention to downstream changes of bed material rather than sediment sorting according to bed configuration. Generally, the upstream part of bars was chosen as a sampling site because it contains the coarsest gravel and exhibits little sorting.

Nine bars 1 to 5km apart were selected randomly for sampling (**table 2.1**, **figs. 2.2 and 2.3**).

Table 2.1 Sample locations

Sampling site	Downstream distance from Kiryu	Details of location	Sampling date
No.1	4.9km	Upstream side of bar near left bank, ≃300m downstream from the Matsubara Bridge.	15th Jan. 1989
No.2	7.1km	Upstream side of island bar near left bank, ≃700m upstream from the Hajika Bridge.	10th Oct. 1988
No.3	9.7km	Upstream side of bar near left bank, ≃600m upstream from the Kashima Bridge.	14th Jan. 1989
No.4	13.2km	Right side of bar on left bank, just upstream side of the wooden Midori Bridge.	8th Oct. 1988
No.5	15.6km	Upstream side of island bar near left bank, ≃400m downstream from the Tanaka Bridge.	14th Jan. 1989
No.6	20.9km	Right side of point bar on left bank, ≃100m downstream from the Kawasaki Bridge.	8th Oct. 1988
No.7	21.7km	Upstream end of point bar on left bank.	15th Jan. 1989
No.8	24.5km	Left side of bar on right bank ≃300m downstream from Watarase Oh-hashi (bridge).	10th Oct. 1988
No.9	25.2km	Upstream part of island bar in middle of river, ≃50m upstream from the wooden Bridge called Takahashi.	11th Jan. 1989

These sites are called No.1 to No.9 in downstream order. Sampling sites were selected to satisfy four conditions; **i)** lack of evidence of artificial disturbance of bed material, **ii)** absence of thick vegetation covering the bar surface which would indicate that bed materials had not moved in several years, **iii)** adequate distance between sampled bars in order to measure any downstream decrease of gravel diameter, and **iv)** convenient access.

Subsurface material was sampled in bulk to a depth of a few times the largest gravel diameter from a $1m^2$ area from which all surface material was removed (e.g. Kellerhals and Bray, 1971). Sampled materials were then sieved and weighed (**fig. 2.4**). Enough material was obtained to ensure that the weight of the largest particle was not more than 2% of the total weight of the sample, except at Site No.1 (less than 5%). **Table 2.2** shows the total sample weight.

Grain size analysis was carried out with a set of 0.5ϕ - ($\sqrt{2}$ mm) scale Tyler Screens. Particles larger than -7.0ϕ were measured directly with a scale (median diameter). Material coarser than -2.0ϕ was sieved in the field; that finer than -2.0ϕ was weighed in the field and subsamples were brought to the laboratory to be dried and sieved. Materials finer than 4.0ϕ was weighed as a whole.

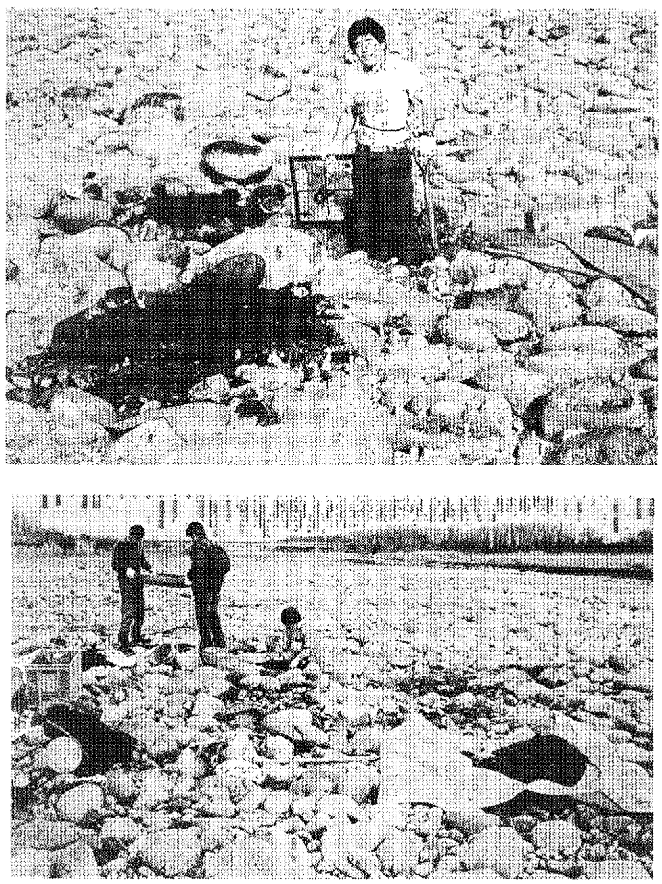


Fig.2.4 Sampling and sieving method of bed material. Sampling at site No.1 (top) and sieving at site No.3 (bottom).

Table 2.2 Grain size of bed material of the Watarase River.

Sampling site Distance from Kiryu	No.1 4.9km		No.2 7.1km		No.3 9.7km		No.4 13.2km		No.5 15.6km		No.6 20.9km		No.7 21.7km		No.8 24.5km		No.9 25.2km	
Grain size ϕ	Percentages retained and cumulative percentages																	
−8.5< <−8.0	12.45	12.45	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
−8.0< <−7.5	9.06	21.51	1.79	1.79	12.12	12.12	3.46	3.46	4.58	4.58	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
−7.5< <−7.0	12.92	34.44	4.60	6.39	12.20	24.32	7.82	11.28	4.39	8.97	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
−7.0< <−6.5	7.72	42.16	6.66	13.05	12.08	36.40	10.94	22.22	11.40	20.38	3.74	3.74	1.43	1.43	0.00	0.00	0.00	0.00
−6.5< <−6.0	8.03	50.20	14.40	27.44	9.77	46.17	6.59	28.81	13.58	33.96	9.07	12.81	9.06	10.49	0.42	0.42	0.00	0.00
−6.0< <−5.5	5.66	55.85	12.17	39.61	7.79	53.96	9.44	38.24	10.77	44.73	15.67	28.48	13.68	24.17	6.64	7.06	1.77	1.77
−5.5< <−5.0	6.52	62.37	13.13	52.74	7.15	61.11	8.32	46.56	9.53	54.25	10.94	39.42	13.68	37.86	12.54	19.60	7.58	9.34
−5.0< <−4.5	5.59	67.96	9.83	62.57	5.96	67.07	6.11	52.68	6.74	60.99	7.97	47.39	9.10	46.96	8.79	28.39	19.93	29.28
−4.5< <−4.0	3.98	71.94	5.15	67.71	4.27	71.34	3.57	56.25	4.69	65.68	4.92	52.31	6.60	53.56	6.45	34.85	11.63	40.91
−4.0< <−3.5	4.38	76.32	6.91	74.62	4.18	75.52	4.63	60.88	4.36	70.04	6.24	58.55	6.24	59.79	7.02	41.86	7.99	48.90
−3.5< <−3.0	2.75	79.07	4.62	79.25	2.81	78.33	4.75	65.63	3.18	73.22	5.14	63.69	5.17	64.97	5.99	47.85	6.67	55.56
−3.0< <−2.5	3.46	82.53	3.99	83.24	3.52	81.85	1.56	67.19	2.87	76.09	6.13	69.82	4.26	69.22	5.75	53.60	6.64	62.21
−2.5< <−2.0	2.64	85.17	3.85	87.09	2.70	84.56	2.88	70.07	2.65	78.74	1.62	71.44	3.82	73.04	5.19	58.79	4.80	67.01
−2.0< <−1.5	1.09	86.26	1.06	88.15	1.54	86.10	2.52	72.59	1.09	79.83	2.56	74.00	1.48	74.51	3.53	62.32	3.41	70.43
−1.5< <−1.0	1.69	87.96	2.36	90.51	2.37	88.47	2.63	75.22	2.27	82.10	3.25	77.25	2.99	77.50	3.72	66.04	2.17	72.59
−1.0< <−0.5	2.10	90.06	2.22	92.73	2.20	90.67	3.17	78.39	2.64	84.75	4.87	82.12	3.82	81.32	3.97	70.01	1.95	74.54
−0.5< < 0.0	2.05	92.11	1.48	94.21	1.68	92.35	3.28	81.66	2.44	87.19	5.39	87.51	4.50	85.82	4.67	74.68	2.46	77.00
−0.0< <+0.5	2.47	94.58	0.94	95.15	1.77	94.12	2.87	84.54	2.87	90.06	3.57	91.08	5.04	90.86	6.42	81.10	5.31	82.31
+0.5< <+1.0	1.92	96.49	1.30	96.45	1.65	95.77	3.60	88.13	2.60	92.66	2.94	94.02	3.28	94.14	8.51	89.62	7.12	89.43
+1.0< <+1.5	1.86	98.36	1.23	97.68	1.93	97.70	3.09	91.22	3.20	95.86	1.78	95.80	2.93	97.07	5.48	95.10	5.93	95.36
+1.5< <+2.0	0.91	99.27	1.19	98.88	1.16	98.86	3.90	95.12	2.01	97.87	2.29	98.09	1.70	98.77	3.33	98.42	2.64	98.00
+2.0< <+2.5	0.42	99.69	0.56	99.44	0.68	99.54	2.37	97.49	1.20	99.07	1.07	99.16	0.84	99.61	1.05	99.47	1.31	99.31
+2.5< <+3.0	0.13	99.82	0.22	99.65	0.23	99.77	1.03	98.52	0.35	99.42	0.39	99.55	0.22	99.83	0.33	99.80	0.33	99.64
+3.0< <+3.5	0.09	99.91	0.17	99.83	0.13	99.89	0.80	99.32	0.27	99.69	0.24	99.79	0.09	99.92	0.14	99.94	0.18	99.82
+3.5< <+4.0	0.05	99.96	0.11	99.94	0.05	99.94	0.29	99.62	0.14	99.83	0.09	99.88	0.03	99.95	0.03	99.98	0.07	99.89
+4.0< <	0.04	100.00	0.06	100.00	0.06	100.00	0.38	100.00	0.17	100.00	0.12	100.00	0.05	100.00	0.02	100.00	0.11	100.00
Weight of sample Median diameter	613.6kg 66.0mm		363.3kg 35.0mm		562.1kg 55.0mm		358.2kg 26.5mm		362.2kg 38.0mm		363.8kg 19.0mm		272.6kg 19.0mm		213.8kg 6.8mm		48.16kg 10.5mm	

ii) Results

Table 2.2 shows the results of the grain size analysis of the bed material in the Watarase River. The size of the gravel decreases fairly rapidly downstream (**fig. 2.5**). In the upstream part, a mode exists at -7.5ϕ to -7.0ϕ. In downstream sites (e.g. No.9), there is a mode at -5.0ϕ to -4.5ϕ and a sand mode which becomes more conspicuous downstream. That is to say, unimodal bed material becomes bimodal downstream.

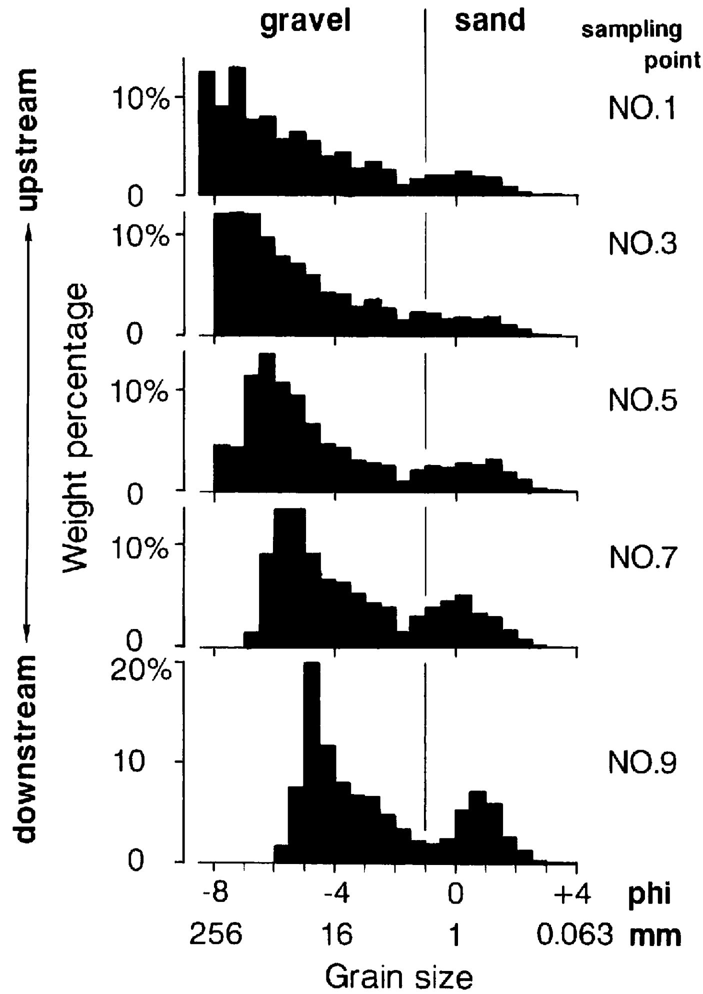


Fig.2.5 Grain size distributions of the Watarase River bed materials. Only odd numbered sampling sites were selected in order to make the downstream tendency clear. The weight percentages of the -1.5ϕ to -2.0ϕ class show lower values between No.1 and No.8 sampling sites. This is because the opening of the -2.0ϕ sieve used in the field was a little smaller than 4mm. In other words, part of the weight percentages of the -2.0ϕ to -2.5ϕ class should be moved to the -1.5ϕ to -2.0ϕ. In sampling site No.9, all the samples were brought to the laboratory and analyzed with correct sieves.

Figure 2.6 shows the longitudinal changes of the median diameter of bed material in the Watarase River. Generally, median diameter decreases exponentially downstream according to Sternberg's law. The rate of size diminution obtained by least-squares regression is expressed as

$$D = 65\ e^{\ 0.089X}$$

where D expresses median diameter in mm at X km downstream from site No.1. The size diminution coefficient of the study reach is 0.089km ^{1}.

2.2.2. Lithologic composition according to grain size

i) Procedures

The author classified sampled gravels larger than -3.5ϕ into four lithologies: **i)** andesite, **ii)** quartz-porphyry and other igneous rocks, **iii)** sandstone & hornfels, and **iv)** chert.

After sieving, all sampled gravels larger than -4.0ϕ were divided into four lithologies and lithologic composition by weight of each grain size at every sampling site was determined. To ensure adequate sample size, more than 1000 particles (Yatsu, 1951) in each -4.0ϕ to -3.5ϕ size sample were divided into four groups according to their lithology, and weighed.

ii) Downstream change of lithologic composition

Lithologic composition of gravel changes dramatically along the 20km reach from sites No.1 to No.9 (**figs. 2.7 and 2.8, table 2.3**). In the upstream part of the study reach, andesite forms most of the boulders. In the downstream part, chert makes up the framework gravels and andesite gravel nearly

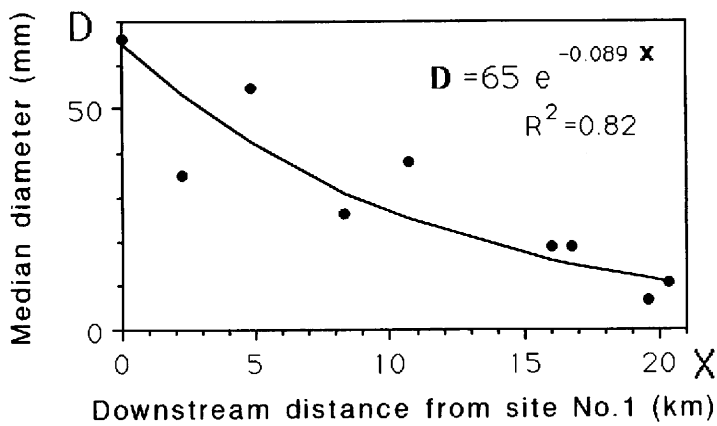


Fig.2.6 Longitudinal changes in the median diameter of the river-bed materials of the Watarase. The median diameter was calculated according to plots on probability paper. Sites No.2 and No.4 show smaller median diameters than the general trend. The author thinks that this aberration is a result of sampling site properties. For example, the gravel bar on which the No.2 sample came from, was deposited by the flood of September 9, 1988. According to the flood discharge data, 1947–1990, (the Watarase River Work Office, Kanto Regional Construction Bureau, the Ministry of Construction), this flood was relatively small having a peak discharge at Ashikaga of 450m^3/sec, and was the maximum flood in 1988. The author related the aberration at site No.4 to some local hydraulic conditions.

disappears (**fig. 2.7**). The amount of andesite in gravel-bed material decreases downstream, while chert gravel increases (**fig. 2.8**). **Figure 2.9** shows the lithologic composition of gravel larger than -3.5ϕ. The andesite fraction which is about 33% in the upstream reach decreases to about 2% at the downstream end. In contrast, the chert fraction increases from about 6% to 30%. The fractions of both quartz-porphyry and sandstone & hornfels decrease slightly downstream.

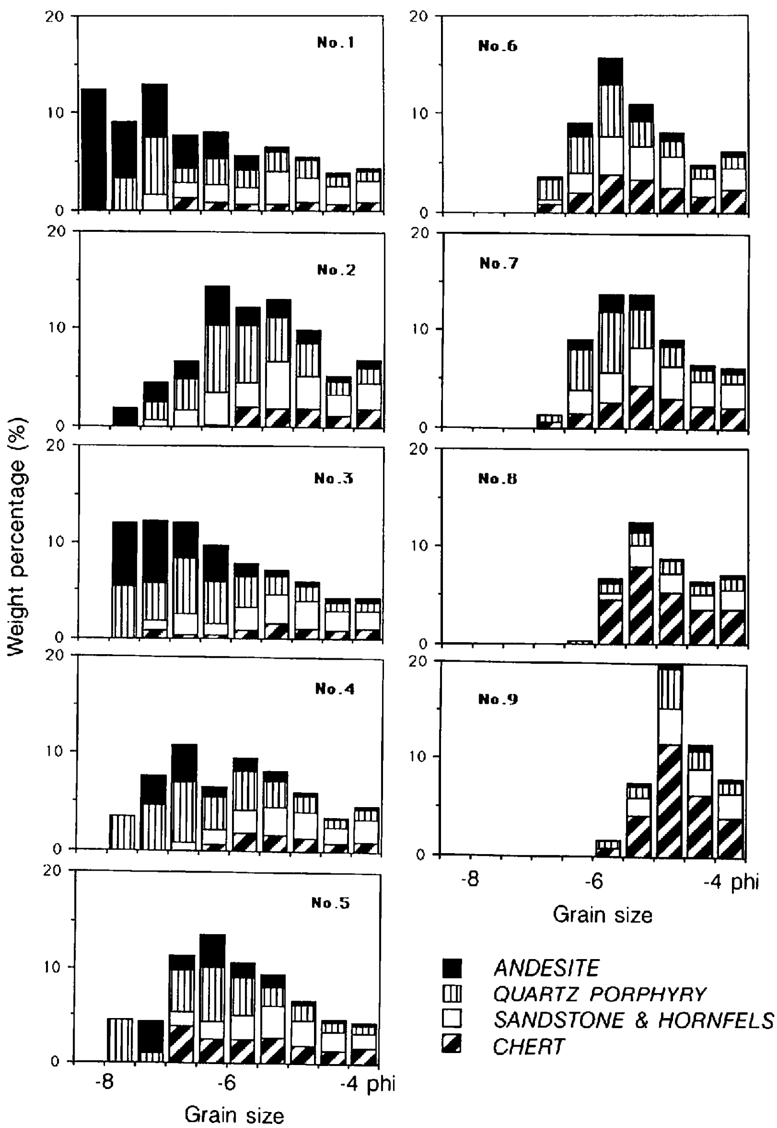


Fig.2.7 Lithologic composition and size of gravel of the Watarase River. This figure was illustrated by selecting sizes larger than -3.5ϕ from **fig.2.5** and showing the lithologic composition in each histogram.

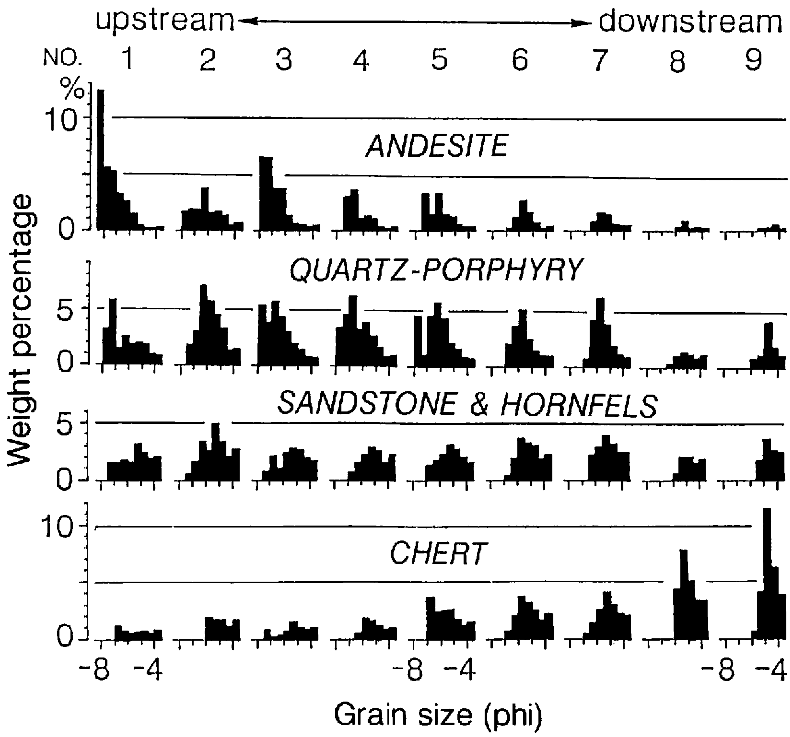


Fig.2.8 Downstream changes in particle size of different lithologies in the Watarase River. This figure was drawn by decomposing bars of **fig.2.7** according to the lithology.

Another point that should be emphasized here is that andesite gravel particles smaller than -5.5ϕ are very rare in the bed material (**Fig. 2.8**). This is a common property of andesite gravel (Koide, 1952, p.64; Komine, 1954; Tada, 1964, pp.97–101) and may become an important factor in the rapid downstream decline in the andesite fraction.

iii) The effect of abrasion on downstream changes in grain size of different lithologies

It is impossible to explain the rapid changes in lithologic composition in the study reach as shown in **figs. 2.7～2.9** only by sorting processes. If the changes in lithologic composition were caused by a sorting process, we would expect to find in every lithologic group the same weight ratio in each grain size class along the study reach.

Lithologic proportions expressed as the weight ratio to chert in each grain size class were compared among nine sites (**fig. 2.10**). All non-chert lithologies in every size show declining proportions downstream. For example, quartz-porphyry gravels of size -6.0ϕ to -5.5ϕ are more than three times as abundant as chert gravels of the same size in the upstream site, but decrease to equal abundance at about 20km downstream. These results clearly indicate that particle abrasion does occur in the Watarase River and is responsible, at least in part, for the downstream decrease in particle size of bed material.

Table 2.3 Lithology and grain size of the gravel coarser than -3.5ϕ.

Sampling site : **No.1**, Distance from Kiryu: 4.9km

Grain size φ	An	QP	S&H	Ch
−8.5< <−8.0	12.5	0.0	0.0	0.0
−8.0< <−7.5	5.7	3.3	0.0	0.0
−7.5< <−7.0	5.3	5.9	1.7	0.0
−7.0< <−6.5	3.3	1.5	1.6	1.3
−6.5< <−6.0	2.7	2.6	1.9	0.8
−6.0< <−5.5	1.5	1.9	1.7	0.6
−5.5< <−5.0	0.5	2.0	3.3	0.7
−5.0< <−4.5	0.3	1.9	2.5	0.8
−4.5< <−4.0	0.3	1.0	2.0	0.6
−4.0< <−3.5	0.4	0.9	2.2	0.9
*total (%)	32.5	21.0	16.9	5.7

Sampling site : **No.2**, Distance from Kiryu: 7.1km

Grain size φ	An	QP	S&H	Ch
−8.5< <−8.0	0.0	0.0	0.0	0.0
−8.0< <−7.5	1.8	0.0	0.0	0.0
−7.5< <−7.0	2.0	1.9	0.7	0.0
−7.0< <−6.5	1.9	3.1	1.7	0.0
−6.5< <−6.0	3.9	6.9	3.5	0.1
−6.0< <−5.5	1.7	5.9	2.6	2.0
−5.5< <−5.0	1.8	4.5	5.0	1.8
−5.0< <−4.5	1.4	3.3	3.4	1.8
−4.5< <−4.0	0.5	1.4	2.1	1.2
−4.0< <−3.5	0.8	1.5	2.8	1.8
*total (%)	15.8	28.5	21.8	8.7

Sampling site : **No.3**, Distance from Kiryu: 9.7km

Grain size φ	An	QP	S&H	Ch
−8.5< <−8.0	0.0	0.0	0.0	0.0
−8.0< <−7.5	6.6	5.5	0.0	0.0
−7.5< <−7.0	6.5	3.9	0.9	0.9
−7.0< <−6.5	3.8	5.8	2.2	0.3
−6.5< <−6.0	3.8	4.4	1.1	0.4
−6.0< <−5.5	1.4	3.1	2.5	0.8
−5.5< <−5.0	0.7	2.0	2.9	1.6
−5.0< <−4.5	0.6	1.5	2.8	1.1
−4.5< <−4.0	0.4	0.9	2.0	0.9
−4.0< <−3.5	0.5	0.8	1.8	1.1
*total (%)	24.3	27.9	16.2	7.1

Sampling site : **No.4**, Distance from Kiryu: 13.2km

Grain size φ	An	QP	S&H	Ch
−8.5< <−8.0	0.0	0.0	0.0	0.0
−8.0< <−7.5	0.0	3.5	0.0	0.0
−7.5< <−7.0	3.1	4.7	0.0	0.0
−7.0< <−6.5	3.8	6.3	0.8	0.0
−6.5< <−6.0	1.1	3.3	1.6	0.6
−6.0< <−5.5	1.3	4.0	2.3	1.9
−5.5< <−5.0	1.1	2.7	2.9	1.6
−5.0< <−4.5	0.4	1.7	2.7	1.3
−4.5< <−4.0	0.2	0.9	1.6	0.9
−4.0< <−3.5	0.4	1.0	2.3	1.0
*total (%)	11.4	28.1	14.2	7.3

Sampling site : **No.5**, Distance from Kiryu: 15.6km

Grain size φ	An	QP	S&H	Ch
−8.5< <−8.0	0.0	0.0	0.0	0.0
−8.0< <−7.5	0.0	4.6	0.0	0.0
−7.5< <−7.0	3.4	1.0	0.0	0.0
−7.0< <−6.5	1.5	4.6	1.5	3.8
−6.5< <−6.0	3.4	5.8	1.9	2.5
−6.0< <−5.5	1.5	4.3	2.4	2.6
−5.5< <−5.0	1.3	2.2	3.4	2.7
−5.0< <−4.5	0.6	1.6	2.8	1.8
−4.5< <−4.0	0.4	0.9	2.1	1.3
−4.0< <−3.5	0.4	0.8	1.6	1.6
*total (%)	12.5	25.8	15.7	16.3

Sampling site : **No.6**, Distance from Kiryu: 20.9km

Grain size φ	An	QP	S&H	Ch
−8.5< <−8.0	0.0	0.0	0.0	0.0
−8.0< <−7.5	0.0	0.0	0.0	0.0
−7.5< <−7.0	0.0	0.0	0.0	0.0
−7.0< <−6.5	0.3	2.1	0.5	0.8
−6.5< <−6.0	1.3	3.7	2.0	2.1
−6.0< <−5.5	2.8	5.2	3.8	3.9
−5.5< <−5.0	1.7	2.5	3.4	3.3
−5.0< <−4.5	0.8	1.5	3.1	2.6
−4.5< <−4.0	0.3	1.1	1.9	1.6
−4.0< <−3.5	0.5	1.1	2.3	2.3
*total (%)	7.7	17.2	17.0	16.6

Sampling site : **No.7**, Distance from Kiryu: 21.7km

Grain size φ	An	QP	S&H	Ch
−8.5< <−8.0	0.0	0.0	0.0	0.0
−8.0< <−7.5	0.0	0.0	0.0	0.0
−7.5< <−7.0	0.0	0.0	0.0	0.0
−7.0< <−6.5	0.0	0.8	0.0	0.6
−6.5< <−6.0	0.9	4.3	2.3	1.5
−6.0< <−5.5	1.7	6.3	3.0	2.7
−5.5< <−5.0	1.5	3.9	4.0	4.3
−5.0< <−4.5	0.7	2.0	3.3	3.1
−4.5< <−4.0	0.6	1.2	2.5	2.3
−4.0< <−3.5	0.6	1.0	2.5	2.2
*total (%)	6.0	19.5	17.6	16.7

Sampling site : **No.8**, Distance from Kiryu: 24.5km

Grain size φ	An	QP	S&H	Ch
−8.5< <−8.0	0.0	0.0	0.0	0.0
−8.0< <−7.5	0.0	0.0	0.0	0.0
−7.5< <−7.0	0.0	0.0	0.0	0.0
−7.0< <−6.5	0.0	0.0	0.0	0.0
−6.5< <−6.0	0.0	0.4	0.0	0.0
−6.0< <−5.5	0.4	1.1	0.7	4.5
−5.5< <−5.0	1.0	1.5	2.1	7.9
−5.0< <−4.5	0.2	1.2	2.1	5.2
−4.5< <−4.0	0.4	0.9	1.6	3.5
−4.0< <−3.5	0.3	1.2	2.0	3.5
*total (%)	2.3	6.3	8.5	24.6

Sampling site : **No.9**, Distance from Kiryu: 25.2km

Grain size φ	An	QP	S&H	Ch
−8.5< <−8.0	0.0	0.0	0.0	0.0
−8.0< <−7.5	0.0	0.0	0.0	0.0
−7.5< <−7.0	0.0	0.0	0.0	0.0
−7.0< <−6.5	0.0	0.0	0.0	0.0
−6.5< <−6.0	0.0	0.0	0.0	0.0
−6.0< <−5.5	0.0	0.9	0.0	0.8
−5.5< <−5.0	0.3	1.2	1.9	4.2
−5.0< <−4.5	0.4	4.2	3.7	11.6
−4.5< <−4.0	0.6	1.9	2.7	6.4
−4.0< <−3.5	0.3	1.1	2.6	4.0
*total (%)	1.6	9.3	10.9	27.0

An: andesite, QP: quartz-porphyry, S&H: sandstone and hornfels, Ch: chert.

*Summing the total weight percentage of 4 lithologies at each site equals the cumulative percentage of -3.5ϕ ~ 4.0ϕ **(table 2.2)** respectively.

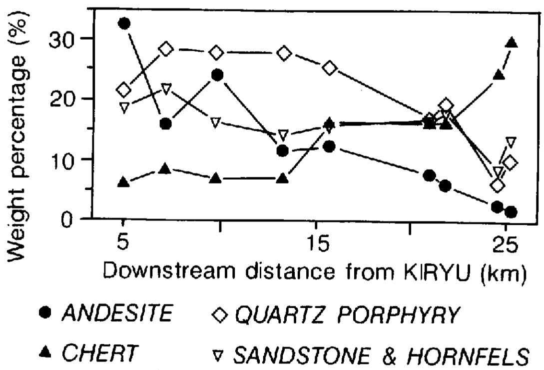


Fig.2.9 Downstream changes of lithologic composition of gravel in the Watarase River. Weight percentage shows the ratio between weight of particles larger than -3.5ϕ of each lithology and the total weight of sampled material at each sampling site.

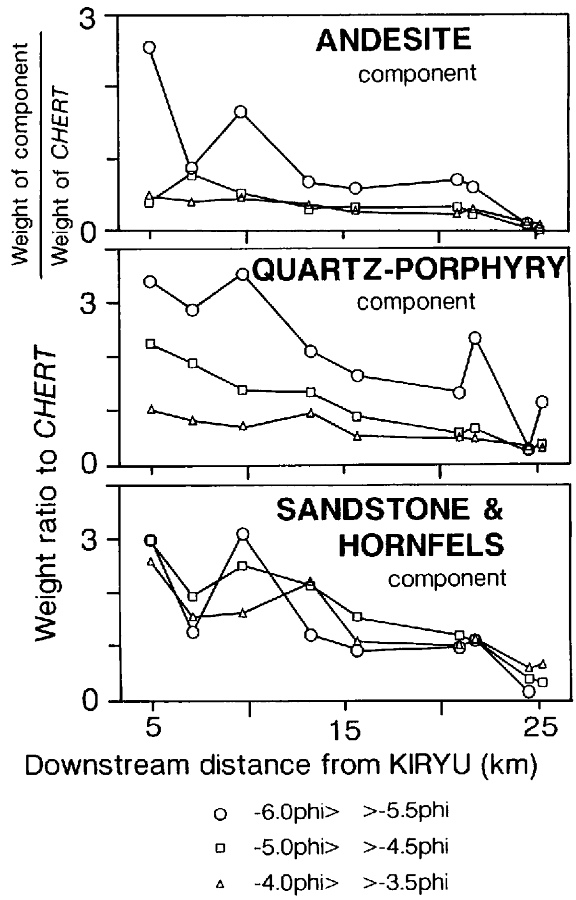


Fig.2.10 Downstream changes of the weight ratio to chert. Only 3 size classes are shown in order to avoid complications.

2.3 Summary

The grain size distribution and lithologic composition of river-bed material were examined along the Watarase River on an alluvial fan (**figs. 2.1~2.3**). This study reach might be regarded to be in an equilibrium state, because the river bed profile has remained nearly constant during the last one thousand years. Bed gravel consists of four types of lithology: **i)** andesite, **ii)** quartz-porphyry and other igneous rocks, **iii)** sandstone and hornfels, and **iv)** chert. Contamination from tributaries has very little effect because tributaries deliver a minor amount of sediment to the Watarase.

Grain size distributions (**fig. 2.5**) show a weak bimodality in the upstream reach, and become strongly bimodal downstream. Granule and coarse sand are the deficient size in the lower Watarase. Moreover, the size diminution coefficient of the lower Watarase obtained from the median diameter (**fig. 2.6**) is about 0.089 (km^{-1}).

Size distribution of gravel is strongly related to the lithologic composition (**fig. 2.7**). Namely, andesite boulders and large cobbles make up the framework sizes in the upstream part, while chert pebbles make up the framework sizes in the downstream part. There are few andesite pebbles and few chert boulders in the river-bed (**figs. 2.8 and 2.9**). Andesite and chert gravels show contrasting characteristics in size distributions which might reflect different abrasion properties.

Longitudinal changes in the lithologic composition of each grain size class (**fig. 2.10**) show that selective transport by lithology occurrs in every gravel size. Abrasion must occur, because for a given grain size there is no reason why a particular lithology would be selectively transported.

CHAPTER III

ERC ABRASION MIXER EXPERIMENT

3.1 Controversial points in previous studies on abrasion experiments

It is very difficult to measure abrasion of gravel during a flood in the field. Therefore it is useful to examine the manner and rate of abrasion in laboratory experiments. Since Daubrée's (1879) study, many researchers (cf. **Chapter 1.2**) performed abrasion experiments with either tumbling mills of various designs (variously called tumbling barrel, rotating drum, rotating cylinder) or circular flumes (Kuenen-type abrasion tank).

The amount of abrasion obtained by previous experiments do not fully explain diminution coefficients occurring in natural rivers (Shaw and Kellerhals; 1982). Consequently many have concluded that abrasion has a minor effect on downstream fining in alluvial rivers.

Previous experiments do not accurately replicate the grain-to-grain impacts in a natural river. There are four issues in abrasion experiments. **i)** The magnitude of impacts of gravel particles in previous studies is much smaller than that in natural rivers during a flood. **ii)** Some researchers have used artificially shaped gravel. **iii)** The duration of experiments has been too long to simulate the abrasion of gravels in natural rivers. **iv)** Since only uniform pebbles have been used in many experiments, it remains unclear how mixed size gravels abrade.

Grain-to-grain impacts on gravel particles in tumbling mills (e.g. Wentworth, 1919; Marshall, 1927, 1929; Krumbein, 1941a) have been fairly low. Particles in the drum tumble down a slope nearly equal to the angle of repose (Kuenen, 1956, fig. 1). The relative velocity between gravels is a few 10cm/sec at most. In experiments using a circular flume (e.g. Kuenen, 1955, 1956; Bradley, 1970; Bradley *et al.*, 1972), individual particles roll on the flume bed at a velocity of about 1 to 2m/sec. These gravel particles do not collide with each other violently, because they are limited in number. They impact a concrete flume floor or pebbles embedded here and there in the floor. As described in **chapter 1.1**, gravel particles transported during floods seem to collide violently with other particles on the bed. No previous experiments have simulated such vigorous collisions except Kodama (1990a) and Mizuyama (1990).

Bradley (1970) points out the importance of experimental materials. Abrasion depends much on the degree of weathering of gravel, and weathering occurs as gravel particles are stored in bars or flood-plains. In this respect, experiments with artificially modified gravel particles that have fresh surfaces cannot properly evaluate the abrasion properties of slightly weathered gravel in natural rivers.

Bradley (1970, pp. 68, 77–78) also mentions duration of experiments in association with the degree of gravel weathering. "Gravel does not move continuously along a river. It spends much of its time in temporary alluvial storage awaiting reworking." During repeated storage in bars or flood-plains, sediments become slightly weathered (Johnson and Stallard, 1989; Johnson, 1990; Johnson and Meade, 1990) and in moving intermittently might be effectively subjected to abrasion. Consequently, data obtained from abrasion experiments of long duration may not replicate nature, because the longer the abrasion experiment is carried out, the more the abraded gravel will be in a state of weathering different from that of a natural river-bed. In other words, the abrasion produced in an experiment is that attributable to one flood in a natural river. Abrasion of slightly weathered gravel has not been examined in detail in previous studies.

Sarmiento (1945) shows the effect of mixture of sizes on abrasion of gravel (Pettijohn, 1957, p.536). Both Marshall (1927) and Kodama (1990a) carry out abrasion experiments using mixed-size gravels with a variety of relative size ratios and examine the mixture effect on abrasion.

The purpose of this experiment is to evaluate abrasion properties quantitatively by more closely simulating the impact occurring on gravel particles in natural rivers according to the four problems mentioned above.

3.2 Experimental materials

3.2.1. Gravel lithology and size

Figure 3.1 shows an example of the experimental materials. All samples were either andesite or chert particles collected from the bed of the Watarase River (from the bar at site No.3; see **table 2.1**, **figs. 2.2 and 2.3**). Three sizes denoted as L, M, S, respectively were used: -7.0ϕ to -6.5ϕ, -5.5ϕ to -5.0ϕ, -4.0ϕ to -3.5ϕ.

Samples were collected from the subsurface in the same manner described in **chapter 2.2.1**. In order to examine abrasion properties lithologically, andesite and chert gravels were picked out one by one from the variety of lithologies in the three sizes mentioned above. This laborious simple work took enormous time. In particular, the amount of S-size andesite is so low in the bed material that huge amounts of subsurface material had to be excavated and sieved to get enough experimental material. In fact, S-size andesite from nine sites in **chapter 2.2.2** which had already been divided into four lithologies to examine the composition of the river-bed material were also added to the samples in order to economize time and labour. But the amount of S-size andesite added from the nine sites was about 25% of the total S-size andesite gravel prepared for experiments.

Gravel sampled from the river-bed was used without any artificial modification as experimental material in order to include the effect of weathering on abrasion processes. This gravel was slightly weathered. Approximately 30kg gravel (dry weight) was prepared for each case. For mixtures of two gravel sizes, about 15kg of each size were prepared. L-size gravels were sampled more for further supplementary experiments. Mud adhering to gravel was washed off before experiments.

3.2.2. Compressive strength of irregularly shaped saturated gravel

In order to know the strength of gravel used in the experiment, irregularly shaped gravel particles were collected from the river-bed to examine their compressive strength. After particles were immersed

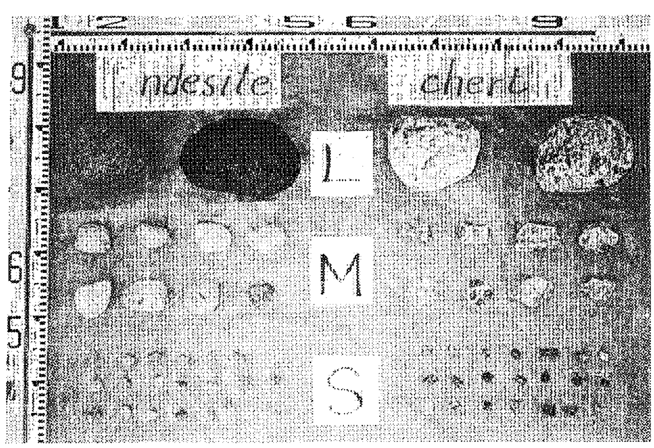


Fig.3.1 Experimental gravel (see text for explanation of L, M, S).

in water for more than 48 hours, a uniaxial compressive test was conducted to obtain the compressive strength of each gravel size and each lithology under saturated conditions. More than fifty particles of each size and lithology were tested and analyzed according to the method of Protod'yakonov (1960).

The values of the compressive strength of chert generally scatter over a wider range than those of andesite (**fig. 3.2, appendix III**). Mean values of each size and lithology were plotted in **fig. 3.3** to show the size effect on the compressive strength. Compressive strength increases with decreasing grain size more rapidly for chert than for andesite. The compressive strength of chert is about twice that of andesite at size S, but is nearly equal to that of andesite at size L.

Sections of gravel split by the compressive test showed that weathering of chert and andesite was different: a reddish brown colored area due to weathering was present in almost all chert particles; most andesite particles were gray throughout indicating that it was fresh, although a few andesite particles had a reddish brown weathering rind. Chert particles did not always split along a plane parallel to the compressive axis, while andesite particles did. Chert particles apparently split along discontinuous planes, such as joints and bedding planes, which control the resistant strength against impact.

3.3 Equipment and procedures

3.3.1 The ERC abrasion mixer

An experimental apparatus was constructed to produce repeated collisions among gravel particles in water (**fig. 3.4**). This apparatus was a partial modification of Kodama's (1990a). The apparatus was a

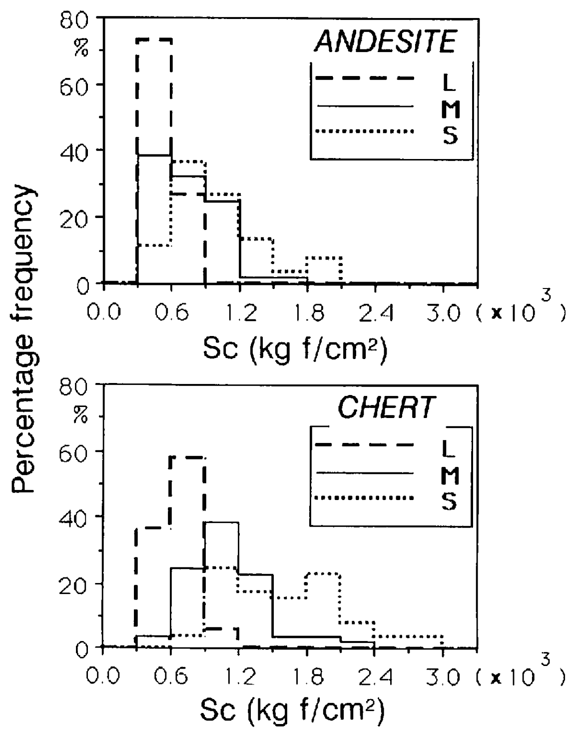


Fig.3.2 Histograms of the compressive strength of each size of gravel. Percentage frequency is calculated by dividing the number of test particles in a class by the total number of particles.

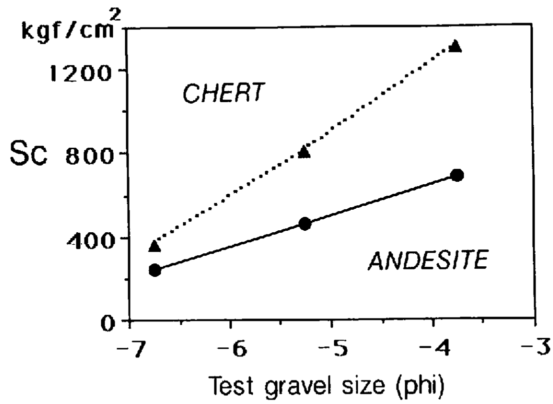


Fig.3.3 Size effect on compressive strength.

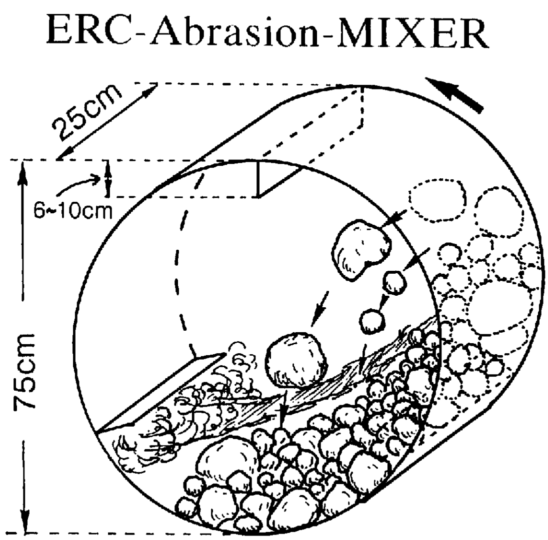
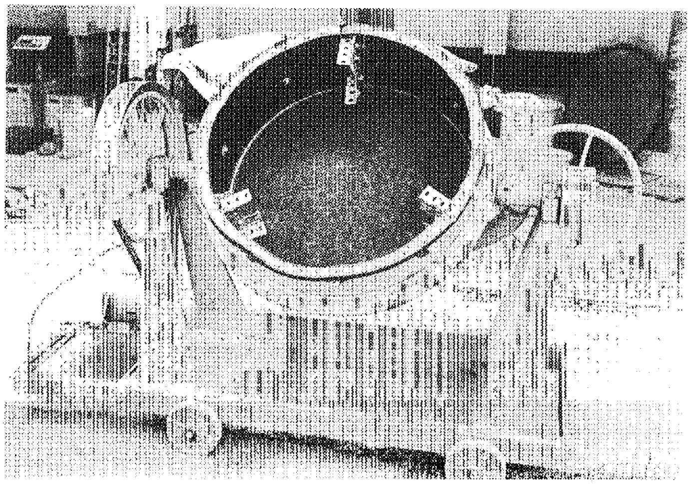


Fig.3.4 Schematic view of the experimental apparatus.

rotating steel cylinder constructed from a concrete mixer. This machine will be called the "**ERC abrasion mixer**" (**ERC** is an acronym for the "**E**nvironmental **R**esearch **C**enter" at Tsukuba Univ. and **MIXER** is an abbreviation of "**M**echanical **I**mpact e**X**plains **E**limination of **R**ocks to sand"). The inside diameter of the drum is 75cm, and its width is 25cm. The width of the drum is narrow so that collisions between gravel particles occur frequently.

Three evenly spaced vanes are attached perpendicular to the circumferential surface of the drum (**fig. 3.5**; top photo). During rotation of the drum, these vanes move the particles up until they drop in the air and impact other particles sitting in water on the bottom of the drum (**fig. 3.4**). A U-shaped vane (**fig. 3.5**; bottom photo) is used because it lifts a portion of the gravel and leaves the remainder and the water behind.

The back side of the drum is made of a plywood plane fixed to the steel circumferential surface, caulked to prevent water leakage and covered with rubber sheets, 2mm in thickness, to prevent gravel



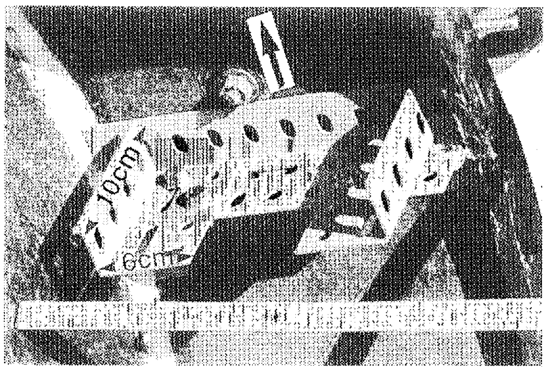


Fig.3.5 The ERC abrasion mixer with vanes attached inside. Top photo: The ERC abrasion mixer was modified from a concrete mixer. We can easily change the direction of the rotation axis by manipulating the handle furnished with the concrete mixer. Rotational speed was controlled with frequency converting equipment (the Mitsubishi Inverter, FR-F_{120}-15K). This abrasion machine has three evenly spaced vanes inside the drum. Rubber sheets were attached in order to prevent abrasion by the metal drum. Bottom photo is shows one vane. It is U-shaped and made of an angle bar.

abrasion against the drum (**fig. 3.5**; top photo). The front side of the drum is a transparent lid, 3mm in thickness, and made of polyvinyl chloride resin through which we could observe the inside of the drum during the experiment. The lid can be attached to and removed from the drum easily. Rubber packing is also used between the drum and the lid to avoid leakage (**fig. 3.7**; top photo).

Rotation of the drum is driven by a motor. The speed of rotation is controlled by an inverter so that a constant speed under any load can be maintained.

3.3.2 Experimental cases

In this study, the author conducted experiments on twelve cases (**table 3.1**) to examine abrasion properties of **i)** both andesite and chert and either alone **ii)** in each gravel size and **iii)** in two-size mix-

Table 3.1 Experimental cases

		ROCK TYPE	
		ANDESITE	CHERT
SAMPLE SIZE	UNIFORM	A-LL	C-LL
		A-MM	C-MM
		A-SS	C-SS
	MIXED	A-LS	C-LS
		A-LM	C-LM
		A-MS	C-MS

A: andesite, C: chert.
L: $-7.0\phi \sim -6.5\phi$, M: $-5.5\phi \sim -5.0\phi$, S: $-4.0\phi \sim -3.5\phi$.

tures.

The author conducted three cases with uniform sizes of andesite **(A)** and chert **(C)**. **LL**, for example, denotes experiments with uniform L-size gravels. All combinations of two sizes: **LS**, **LM**, **MS**, were used with each lithology. In an additional three cases, a mixture of lithologies (number ratio of andesite to chert of 15:5, 10:10, and 5:15) was used with L-size particles.

3.3.3 Experimental procedures

In each case, the author repeated experimental runs 3 to 5 times in order to average the result. Each run was carried out in four steps: **a)** input of test gravel particles and water into the drum, **b)** rotation of the drum, **c)** grain size analysis, and **d)** preparation of gravel for the next run. These procedures will be described in detail.

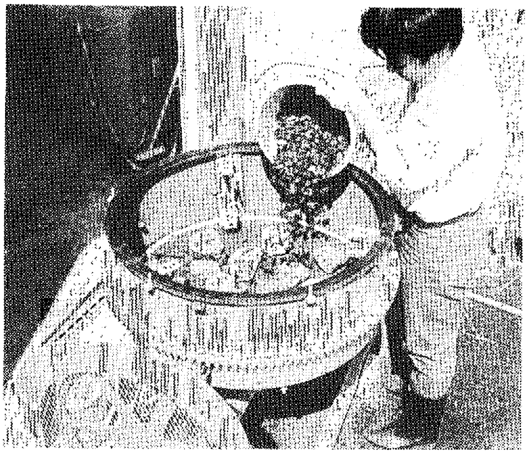
a. Input of test gravel particles and water into the drum

Gravel particles were dried in an oven at 105℃ for several hours before each run. They were weighed to the nearest gram before putting them into the drum with 22 ℓ water **(fig. 3.6)**.

The amount of water poured into the drum was set to produce particle collisions in the drum equal to those in a natural river. If the drum was filled with water, the maximum velocity of falling particles would be less than 1m/sec, the terminal settling velocity of L-size gravel in water. Furthermore water in a natural river flows faster than gravel and impels it to move, whereas the water in the drum works on gravel motion like a brake. In other words, water in a rotating drum plays the opposite role on the gravel motion than in a natural river. Thus the amount of water should be as small as possible just enough to cover the gravel in order to produce particle collisions in water.

b. The operation of the drum

After fixing the lid to the drum **(fig. 3.7**; top), tilting the drum until its rotating axis was nearly horizontal, and confirming that there was no leakage of water, rotation of the drum was commenced **(fig. 3.7**; bottom). The drum was rotated at a speed of 25 rpm in all experiments so that velocity of collisions between particles would be similar to those in a natural river. At this rotation speed, a part of the gravel was elevated to nearly three quarters of the height of the drum before falling. Consequently, the maximum particle velocities attained about 3m/sec.



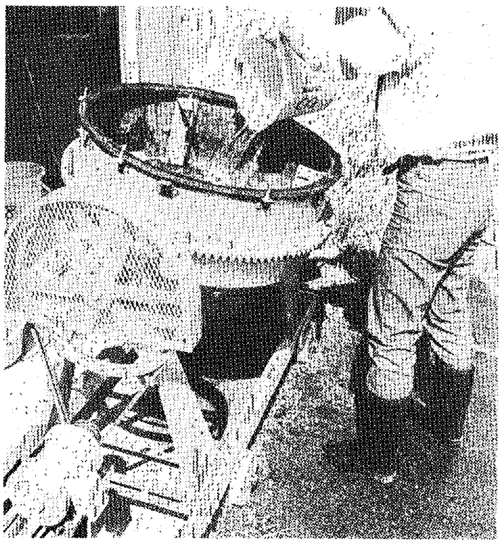
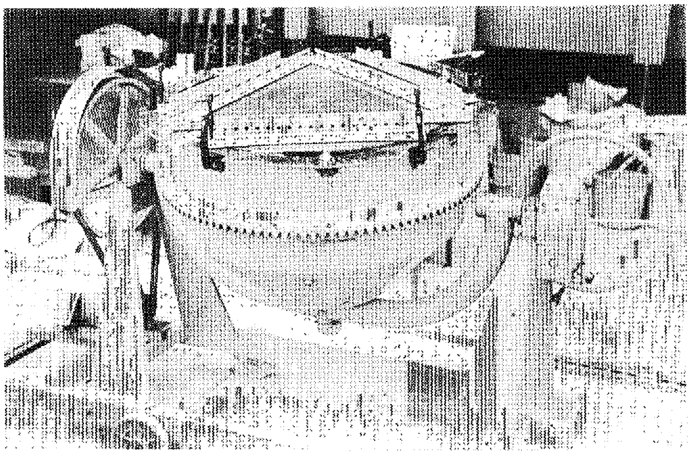


Fig.3.6 Putting test gravels (top photo) and water into the drum (bottom photo) before each run. These photos were taken at a preliminary experiment, so the circumferential surface of the drum had not been covered with rubber yet.

The collision velocity of particles in the Watarase River during floods was estimated as follows. At a flood discharge of more than 1000m^3/sec, depth of water is about 3 to 5m, and maximum stream velocity is about 5m/sec along the thalweg at Ashikaga (personal communication, the Watarase River Work Office, Kanto Regional Construction Bureau, the Ministry of Construction). Under such conditions, gravel particles in motion are assumed to saltate (**fig. 3.8**) after initially rolling (Tsuchiya *et al.*, 1969; Yano *et al.*, 1969; Tsuchiya and Aoyama, 1970; Francis, 1973). According to Bagnold (1973), the transport velocity of saltating solids is equal to the fluid velocity minus the slip velocity which is approximately equal to terminal settling velocity. Assuming that fluid velocity within the saltation zone along



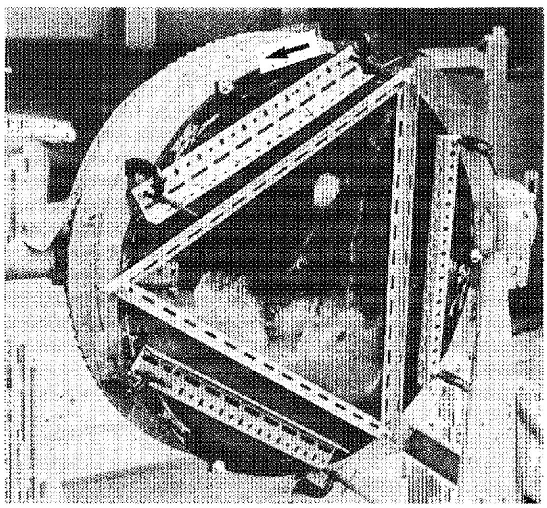


Fig.3.7 Setting and operation of the ERC abrasion mixer.
Top: Fixing the lid to the drum with nuts & bolts, C-clamps and angle bars in order to prevent water leakage.
Bottom: Operation of the ERC abrasion mixer. A particle which was lifted by a vane falls freely in the air and another particle is just penetrating the muddy water. Angle bars are for reinforcing the lid against collisions with particles. Vanes are near the corners of the triangular angle bars.

the thalweg is equal to 4m/sec at maximum, gravels of about 10cm in median diameter (L-size particles) would saltate at a maximum speed of about 3m/sec (the terminal settling velocity of a 10cm median diameter particle is approximately 1m/sec.) and collide with other particles on the bed.

In each run, the drum was operated for three to five minutes, while runs in most previous abrasion experiments have had longer durations of one hour to a few days. More rapid abrasion occurred in the ERC abrasion mixer experiment than in previous ones, due to the severer particle-to-particle impact. During our experiment, clear water became slightly muddy (**fig. 3.7**; bottom photo) within the first one

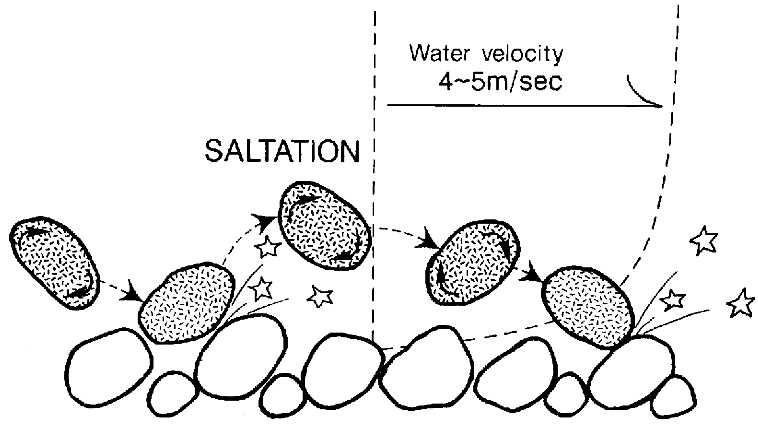


Fig.3.8 Schematic view of the collisions between a saltating gravel particle (hatched one) and particles in the river-bed.

or two minutes of rotating the drum, and became muddier after more time. As the run continued for one or two minutes longer, fragments chipped or split from the test particles were observed dancing violently in the muddy water.

If we had continued our runs for a long time, two problems might arise. First, runs starting with uniform-size material would gradually produce a size mixture as the experiment proceeds, because of the fragments produced by abrasion. This change is inconvenient for gaining an understanding of abrasion under a certain grain size condition. Second, it makes it difficult to interpret the abrasion process from the size distribution of fragments. Small pebbles tend to be crushed so rapidly (Sarmiento, 1945; Kodama, 1990a) that it is difficult to distinguish an abrasion process that produces mainly sand from another that produces small pebbles, because pebbles would soon be crushed to sand, particularly in a closed system such as an abrasion mill.

Considering these issues, the operation of the drum was stopped after three to five minutes in all runs. These durations were long enough to observe fractions split from the test gravel dancing in the muddy water.

c. Grain size analysis after experimental runs

All detritus (including test gravel particles and fragments produced by abrasion) in the drum was retrieved with great care. The procedure was as follows: first, the drum was tilted until the axis was vertical and the lid was removed. At this time, the author detected a smell like grinding a knife with a whetstone. All gravel-sized material was picked out by hand. Fine particles attached to gravel were washed off with the residual muddy water into the drum. Second, fine particles were washed from inside the drum as it was tilted gradually. Finally the remaining fine particles and muddy water in the drum were completely washed by fresh water through a 4ϕ ($63\mu m$) sieve into a bucket. Third, silt content in the muddy water in the bucket was determined by settling for about two hours (Rubey, 1933). Fourth, after one or two weeks settled sediment (clay) on the bottom of the bucket was gathered on an evaporating dish with a little water.

All detritus was dried completely in an oven at 105°C for several hours (sand and gravels) or more than 24 hours (silt and clay). Grain size analysis of gravels was done at 0.5ϕ intervals. Dry weight of sand, silt and clay was measured separately. Weights were measured with an electronic scale to an accuracy of 0.01 gram.

d. Repeatedly used test gravel for runs in each experimental case

Because of the limitation in amount of test gravel, the same gravel particles were used from three to five runs in each case. After the grain size analysis was completed in each run, gravel that remained in the initial size class was used as test gravel for the next run. This means that the amount of test gravel put into the drum decreases little by little according to the run number in each case. The cumulative duration run time of the ERC abrasion mixer experiment in each case was fifteen minutes, which is still shorter than that of previous experiments.

3.4 Results

3.4.1 Data sheets and definition of the terms

The experimental data of all runs in each case are shown in **table 3.2 to table 3.4**. In **tables 3.2 and 3.3**, each run is expressed as "Lithology - Grain size combination - Run number". For example, "A-LL-3" means the third run in L-size uniform case using andesite gravel. In **table 3.4**, which shows data of lithologic mixture cases under L-size uniform conditions, each run is expressed as "**A** the number of andesite gravels, **C** the number of chert gravels - run number". Weight loss during a run was added to the weight of silt and clay while maintaining the weight ratio between them. The weight of the test gravel put into the drum was rounded to the nearest gram.

Test gravels were abraded in each run and yielded particles smaller than the initial 0.5ϕ class (**Tables 3.2 to 3.4**). In this study, these smaller particles are referred to as "produced detritus (fragments)" or "products". The terms of the following two "weight ratios" are used in order to compare quantitatively the abrasion properties of andesite with those of chert. The "weight percentage of products" is the weight of products divided by the initial weight of the test gravel. The difference in weight of gravel before and after an experiment is referred to as "weight loss of test gravel". "Weight loss percentage" equals the weight loss of the test gravel divided by its initial weight.

In uniform-size experiments, the sum of "weight percentage of products" and "weight loss percentage" is 100%. In mixed-size experiments, it is possible that part of the detritus split from larger test gravel falls into a smaller size class of test gravel. Therefore the calculated weight loss of the smaller-size test gravel can be a smaller value than its actual weight loss. The amount of such under-estimation, however, appears negligible (**table 3.3**).

3.4.2 Abrasion properties of andesite and chert

We found three differences and two similarities in the abrasion properties of andesite and chert. They differ in the following respects: **i)** much more gravel-size detritus is produced from chert, while much more sand and silt are produced from andesite; **ii)** in the case of the L size, chert is abraded more rapidly than andesite; and **iii)** in the S size, andesite is abraded more rapidly. Abrasion is similar in the following respects: **iv)** the weight loss percentage becomes large when test gravels are split; and **v)** in LS cases, the effects of mixture of gravel size on abrasion are strong. These abrasion properties are described in detail in the following section.

i) Abrasion properties in LL cases

Figures 3.9 and 3.10 display the size distributions of all produced fragments from the five-minute experiments (C-LL-4 and A-LL-4). Chert produced large gravel fragments, while andesite produc-

Table 3.2 Grain size distributions after each run of the uniform size cases

RUN No. / Experimental time (min)	A-LL-1 / 3	A-LL-2 / 4	A-LL-3 / 3	A-LL-4 / 5	C-LL-1 / 3	C-LL-2 / 3	C-LL-3 / 4	C-LL-4 / 5
Initial Weight of test gravel (g)	30864.	30751.	30532.	30319.	29664.	28134.	28000.	27592.
Grain size after experiment φ								
−7.0< <−6.5	30751.	30532.	30319.	29725.	28134.	28000.	27592.	25962.
−6.5< <−6.0	0.0	0.0	0.0	0.0	774.0	0.0	0.0	1084.6
−6.0< <−5.5	0.0	0.0	0.0	0.0	418.0	0.0	0.0	0.0
−5.5< <−5.0	0.0	0.0	0.0	0.0	93.9	0.0	152.5	220.2
−5.0< <−4.5	0.0	0.0	0.0	14.4	16.5	0.0	49.5	53.6
−4.5< <−4.0	0.0	0.0	0.0	23.5	44.9	0.0	10.2	34.7
−4.0< <−3.5	0.0	0.0	0.0	17.0	21.0	9.6	33.2	24.4
3.5< <−3.0	0.0	1.2	4.0	19.8	29.1	12.9	15.5	21.0
−3.0< <−2.5	0.3	4.6	6.9	24.1	15.2	8.6	11.0	22.3
−2.5< <−2.0	0.3	3.3	8.6	25.2	13.6	9.4	13.5	14.9
−2.0< <−1.5	0.8	3.1	7.5	23.9	14.2	9.3	13.1	14.2
−1.5< <−1.0	1.1	3.7	7.2	28.4	10.9	8.9	11.0	12.6
sand	65.60	142.10	117.83	293.80	59.30	58.00	68.80	92.40
silt	42.69	56.45	57.23	117.04	18.87	16.65	28.44	28.64
clay	2.21	4.55	3.74	6.86	0.53	0.65	1.26	6.46
TOTAL (g)	30864.00	30751.00	30532.00	30319.00	29664.00	28134.00	28000.00	27592.00

RUN No. / Experimental time (min)	A-MM-1 / 3	A-MM-2 / 3	A-MM-3 / 4	A-MM-4 / 5	C-MM-1 / 3	C-MM-2 / 3	C-MM-3 / 4	C-MM-4 / 5
Initial Weight of test gravel (g)	30157.	28874.	28267.	27777.	30047.	29820.	29514.	29003.
Grain size after experiment φ								
−5.5< <−5.0	28874.	28267.	27777.	27082.	29820.	29514.	29003.	28834.
−5.0< <−4.5	951.60	347.50	127.50	300.20	64.31	198.54	299.30	0.00
−4.5< <−4.0	14.01	0.00	27.05	0.00	21.65	5.90	53.27	57.78
−4.0< <−3.5	11.30	0.00	5.63	0.00	31.35	26.20	43.28	7.85
−3.5< <−3.0	6.94	0.00	1.56	3.34	18.56	2.53	12.52	1.00
−3.0< <−2.5	4.74	0.49	0.50	3.58	8.27	2.43	8.97	4.91
−2.5< <−2.0	2.67	0.93	1.04	1.92	5.52	3.18	4.80	5.05
−2.0< <−1.5	1.64	0.68	0.81	0.99	4.34	3.30	3.98	2.61
−1.5< <−1.0	1.56	0.80	1.10	1.48	3.71	2.91	2.60	2.37
sand	169.58	128.42	155.47	182.52	40.80	33.49	45.30	43.74
silt	112.03	124.84	166.19	199.48	25.68	23.97	33.64	39.16
clay	6.93	3.34	3.15	1.49	2.81	3.55	3.34	4.53
TOTAL (g)	30157.00	28874.00	28267.00	27777.00	30047.00	29820.00	29514.00	29003.00

RUN No. / Experimental time (min)	A-SS-1 / 3	A-SS-2 / 3	A-SS-3 / 4	A-SS-4 / 5	C-SS-1 / 3	C-SS-2 / 3	C-SS-3 / 4	C-SS-4 / 5
Initial Weight of test gravel (g)	30000.	29452.	28932.	28464.	30003.	29542.	29247.	28990.
Grain size after experiment φ								
−4.0< <−3.5	29452.	28932.	28464.	27991.	29542.	29247.	28990.	28765.
−3.5< <−3.0	388.88	373.08	333.10	323.19	424.20	272.20	233.81	191.14
3.0< <−2.5	8.12	12.56	6.53	8.89	1.70	0.73	0.50	3.18
−2.5< <−2.0	6.04	7.56	3.54	3.77	1.40	0.92	1.02	1.50
−2.0< <−1.5	5.26	4.00	2.05	2.05	0.38	0.44	0.65	1.20
−1.5< <−1.0	3.30	3.35	1.96	1.63	0.78	0.29	0.34	0.63
sand	41.12	28.80	22.61	21.43	5.59	3.41	1.50	4.58
silt	86.46	73.81	84.58	99.92	22.52	13.44	15.76	20.05
clay	8.82	16.84	13.63	12.12	4.43	3.57	3.42	2.72
TOTAL (g)	30000.00	29452.00	28932.00	28464.00	30003.00	29542.00	29247.00	28990.00

Table 3.3 Grain size distributions after each run of the two-size mixture cases

RUN No. / Experimental time (min)	A-LS-1	A-LS-2	A-LS-3	A-LS-4	A-LS-5	C-LS-1	C-LS-2	C-LS-3	C-LS-4	C-LS-5
Experimental time (min)	3	3	3	3	3	3	3	3	3	3
Initial Weight of test gravel (g)	14965.	14935.	14895.	14850.	14800.	15303.	15263.	15213.	15192.	15122.
	14965.	13252.	11902.	10796.	9874.	15303.	14107.	13142.	12269.	11554.
Grain size after experiment φ										
−7.0< <−6.5	14935.	14895.	14850.	14800.	14749.	15263.	15213.	15192.	15122.	15086.
−6.5< <−6.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
−6.0< <−5.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
−5.5< <−5.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
−5.0< <−4.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
−4.5< <−4.0	0.00	0.00	0.00	0.00	0.00	25.90	20.90	9.50	23.30	0.00
−4.0< <−3.5	13252.	11902.	10796.	9874.	9032.	14107.	13142.	12269.	11554.	10815.
−3.5< <−3.0	883.00	746.50	604.76	504.05	454.81	820.20	586.30	520.10	417.40	499.20
−3.0< <−2.5	338.80	244.10	211.43	174.66	166.65	155.92	160.73	147.74	153.19	102.51
−2.5< <−2.0	133.40	98.43	82.93	69.82	63.99	74.42	77.90	62.27	57.65	50.01
−2.0< <−1.5	59.12	45.58	39.45	33.03	33.53	35.81	38.02	36.33	28.91	26.68
−1.5< <−1.0	39.71	30.00	24.51	29.95	19.89	22.99	24.02	22.37	18.46	15.55
sand	205.50	152.11	131.11	112.77	103.11	75.51	79.12	69.67	64.80	59.07
silt	77.46	67.95	51.60	53.10	47.05	23.32	25.95	23.85	20.05	20.58
clay	6.01	5.33	5.21	3.62	3.97	1.93	2.06	2.17	1.24	1.40
TOTAL (g)	29930.00	28187.00	26797.00	25646.00	24674.00	30606.00	29370.00	28355.00	27461.00	26676.00

RUN No.	A-LM-1	A-LM-2	A-LM-3	A-LM-4	A-LM-5	C-LM-1	C-LM-2	C-LM-3	C-LM-4	C-LM-5
Experimental time (min)	3	3	3	3	3	3	3	3	3	3
Initial Weight of test gravel (g)	15276.	15167.	15096.	14895.	14871.	15261.	15237.	15215.	15189.	15161.
	15276.	15076.	14590.	14227.	13776.	15261.	14676.	14363.	13927.	13493.
Grain size after experiment φ										
−7.0< <−6.5	15167.	15096.	14895.	14871.	14747.	15237.	15215.	15189.	15161.	15133.
−6.5< <−6.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
−6.0< <−5.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
−5.5< <−5.0	15176.	14590.	14227.	13776.	13463.	14676.	14363.	13927.	13493.	13007.
−5.0< <−4.5	43.38	275.79	303.36	233.91	183.18	451.27	205.87	310.67	365.25	378.77
−4.5< <−4.0	9.77	17.80	9.45	0.00	21.74	50.24	14.09	46.40	20.00	43.82
−4.0< <−3.5	10.54	8.83	15.91	7.10	2.64	6.20	12.04	16.11	7.21	14.03
−3.5< <−3.0	6.59	6.07	0.94	11.34	8.53	15.56	14.58	6.36	6.10	6.06
−3.0< <−2.5	4.03	8.78	4.68	2.36	4.44	10.16	7.44	9.50	5.14	5.65
−2.5< <−2.0	2.94	8.37	2.69	1.77	1.90	4.53	5.49	3.99	2.12	2.70
−2.0< <−1.5	2.71	5.99	2.14	1.51	2.38	4.95	3.61	3.75	2.96	2.34
−1.5< <−1.0	3.16	4.95	2.44	1.79	2.66	3.70	4.20	3.17	2.22	2.40
sand	131.17	128.80	130.24	124.02	121.79	37.07	42.07	37.71	28.90	33.11
silt	89.20	86.66	86.50	85.57	83.12	24.12	23.91	22.97	20.83	23.70
clay	5.51	4.96	5.65	5.63	4.62	1.20	1.70	1.37	1.27	1.42
TOTAL (g)	30552.00	30243.00	29686.00	29122.00	28647.00	30522.00	29913.00	29578.00	29116.00	28654.00

RUN No.	A-MS−1	A-MS−2	A-MS−3	A-MS−4	A-MS−5	C-MS−1	C-MS−2	C-MS−3	C-MS−4	C-MS−5
Experimental time (min)	3	3	3	3	3	3	3	3	3	3
Initial Weight of test gravel (g)	15013.	14786.	14586.	14314.	14055.	15000.	14920.	14548.	14324.	14167.
	15013.	14723.	14443.	14238.	14109.	15000.	14813.	14708.	14445.	14286.
Grain size after experiment φ										
−5.5< <−5.0	14786.	14586.	14314.	14055.	13760.	14920.	14548.	14324.	14167.	14091.
−5.0< <−4.5	91.43	141.66	209.65	209.78	232.91	0.00	358.90	206.33	146.56	57.97
−4.5< <−4.0	0.00	0.00	0.00	0.00	0.00	63.37	0.00	0.00	0.00	16.04
−4.0< <−3.5	14723.	14443.	14238.	14109.	13986.	14813.	14708.	14445.	14286.	14150.
−3.5< <−3.0	259.29	187.61	128.67	66.12	74.49	151.70	77.94	242.12	130.54	101.56
−3.0< <−2.5	12.39	12.65	9.86	5.15	5.90	10.29	5.16	5.84	8.55	4.95
−2.5< <−2.0	8.61	6.36	4.48	2.51	2.87	4.70	3.11	4.11	3.71	3.63
−2.0< <−1.5	5.33	4.43	2.95	2.23	2.23	2.84	2.49	2.08	2.41	2.00
−1.5< <−1.0	3.25	2.77	2.11	1.20	0.77	1.74	1.54	1.44	1.14	1.40
sand	44.92	44.64	36.50	33.65	34.56	14.89	11.38	9.79	8.74	8.93
silt	84.14	64.63	73.27	59.87	58.64	15.65	14.38	13.46	12.32	13.09
clay	7.64	15.25	9.51	7.49	5.63	1.82	2.10	1.83	2.03	2.43
TOTAL (g)	30026.00	29509.00	29029.00	28552.00	28164.00	30000.00	29733.00	29256.00	28769.00	28453.00

Table 3.4 Grain size distributions after each run of the lithologic mixture cases

RUN No.	A15C05-1		A15C05-2		A15C05-3	
Lithology	andesite	chert	andesite	chert	andesite	chert
Experimental time (min)	5	5	5	5	5	5
Initial Weight of test gravel (g)	27195.	11676.	26953.	11372.	26639.	11341.
Grain size after experiment φ						
−7.0< <−6.5	26953.	11372.	26639.	11341.	26343.	11211.
−6.5< <−6.0	0.00	0.00	0.00	0.00	0.00	0.00
−6.0< <−5.5	0.00	217.73	0.00	0.00	0.00	89.20
−5.5< <−5.0	0.00	0.00	0.00	0.00	0.00	0.00
−5.0< <−4.5	0.00	0.00	0.00	0.00	0.00	0.00
−4.5< <−4.0	0.00	27.96	0.00	0.00	0.00	5.60
−4.0< <−3.5	0.00	11.15	0.00	0.00	0.00	3.44
−3.5< <−3.0	0.00	9.06	0.00	2.07	0.00	2.44
−3.0< <−2.5	0.00	3.52	0.00	1.97	0.00	3.61
−2.5< <−2.0	0.00	2.80	0.09	0.71	0.08	3.33
−2.0< <−1.5	0.02	2.73	0.24	1.37	0.18	3.47
−1.5< <−1.0	0.17	2.87	0.34	1.01	0.35	2.68
sand, silt & clay	241.81	26.18	313.33	23.87	295.39	16.23
TOTAL (g)	27195.00	11676.00	26953.00	11372.00	26639.00	11341.00
sand	139.90		130.52		212.97	
silt & clay	128.09		206.68		98.65	

RUN No.	A10C10-1		A10C10-2		A10C10-3	
Lithology	andesite	chert	andesite	chert	andesite	chert
Experimental time (min)	5	5	5	5	5	5
Initial Weight of test gravel (g)	21960.	21934.	21642.	21842.	21318.	21782.
Grain size after experiment φ						
−7.0< <−6.5	21642.	21842.	21318.	21782.	20986.	21729.
−6.5< <−6.0	0.00	0.00	0.00	0.00	0.00	0.00
−6.0< <−5.5	0.00	0.00	0.00	0.00	0.00	0.00
−5.5< <−5.0	0.00	0.00	0.00	0.00	0.00	0.00
−5.0< <−4.5	0.00	15.69	0.00	0.00	0.00	0.00
−4.5< <−4.0	0.00	3.34	0.00	0.00	0.00	0.00
−4.0< <−3.5	0.00	5.00	0.00	0.00	0.00	0.00
−3.5< <−3.0	0.00	0.82	0.00	0.00	0.00	0.00
−3.0< <−2.5	0.40	3.84	0.00	1.14	0.00	0.00
−2.5< <−2.0	0.00	5.51	0.32	1.58	0.08	0.58
−2.0< <−1.5	0.19	4.35	0.15	1.61	0.18	1.07
−1.5< <−1.0	0.25	3.71	0.62	2.15	0.35	1.33
sand, silt & clay	317.16	49.74	322.91	53.52	331.39	50.02
TOTAL (g)	21960.00	21934.00	21642.00	21842.00	21318.00	21782.00
sand	197.23		230.98		246.43	
silt & clay	169.67		145.45		134.98	

RUN No.	A05C15-1		A05C15-2		A05C15-3	
Lithology	andesite	chert	andesite	chert	andesite	chert
Experimental time (min)	5	5	5	5	5	5
Initial Weight of test gravel (g)	10910.	32929.	10834.	30757.	10635.	30569.
Grain size after experiment φ						
−7.0< <−6.5	10834.	30757.	10635.	30569.	10505.	30420.
−6.5< <−6.0	0.00	0.00	0.00	0.00	0.00	0.00
−6.0< <−5.5	0.00	0.00	0.00	0.00	0.00	0.00
−5.5< <−5.0	0.00	0.00	0.00	0.00	0.00	0.00
−5.0< <−4.5	0.00	0.00	0.00	0.00	0.00	0.00
−4.5< <−4.0	0.00	0.00	0.00	13.55	0.00	0.00
−4.0< <−3.5	0.00	21.04	0.00	0.00	0.00	4.88
−3.5< <−3.0	0.00	11.89	0.00	9.54	0.00	4.35
−3.0< <−2.5	0.25	9.47	0.00	15.72	0.00	3.81
−2.5< <−2.0	0.00	10.92	0.00	5.78	0.00	5.67
−2.0< <−1.5	0.00	8.34	0.02	8.06	0.00	6.22
−1.5< <−1.0	0.18	9.03	0.19	8.71	0.13	7.17
sand, silt & clay	75.57	101.31	198.79	126.64	129.87	116.90
TOTAL (g)	10910.00	30929.00	10834.00	30757.00	10635.00	30569.00
sand	139.42		170.65		170.73	
silt & clay	37.46		154.78		76.04	

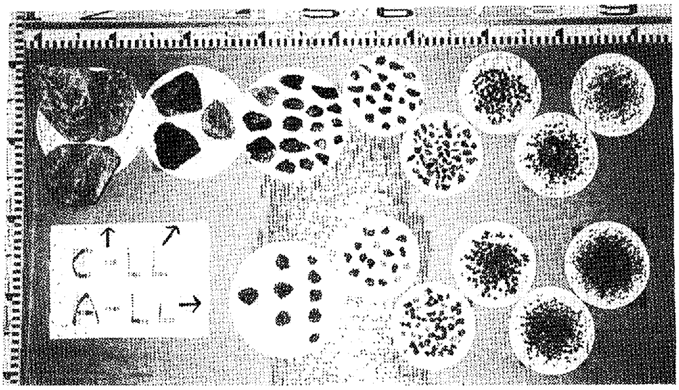


Fig.3.9 Products of gravel fractions in 5-minute ERC abrasion mixer experiments. Upper row is for C–LL–4 and bottom one is for A–LL–4.

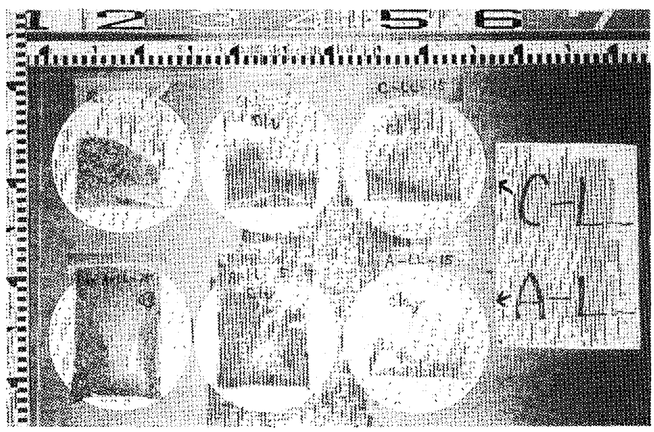


Fig.3.10 Products of fine particles in 5-minute ERC abrasion mixer experiments. Upper row is for C–LL–4 and bottom one is for A–LL–4.

ed detritus smaller than -5.0ϕ (**fig. 3.9**). However, andesite produced slightly more granule-size detritus and much more sand and silt than chert (**fig. 3.10**). Such differences in size distributions of detritus were also shown in other runs of LL cases (**fig. 3.11**).

The rate of production of andesite detritus increased with time (**fig. 3.11**). This is attributed to the following three factors. First, part of the andesite test gravel was chipped during a subsequent run to produce gravel-size fragments smaller than -5.0ϕ. Second, intense granular disintegration occurred at the rough broken surface of this gravel (**table 3.5**; **fig. 3.12**). Third, repeated collisions made the surface of andesite gravel rough and increased granular disintegration from the surface.

The weight percentage of products from chert showed great variety. Since chert gravels in C-LL-1 and in C-LL-4 split into gravel larger than -5.0ϕ, the weight percentages of products, or the weight loss percentages of test gravels were great in these runs. As splitting of gravel proceeded over a wide distribution of probabilities, the weight percentage of products differed greatly from run to run.

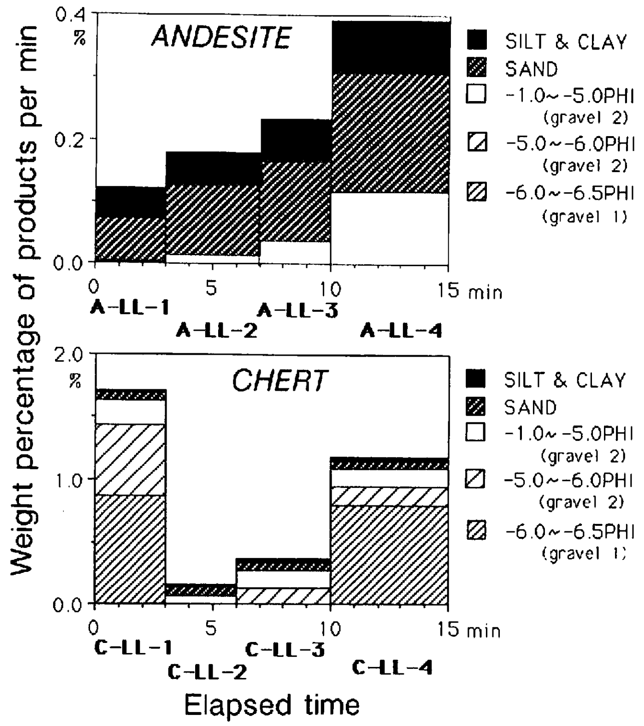


Fig.3.11 Weight percentages of products in each run of L-size uniform cases and their grain size compositions. Width of each bar is proportional to experimental run time (regarding gravel 1 or 2, see text for explanation, and see **appendix IV** for other cases).

Table 3.5 Weight of individual test gravel particles of two runs in the A-LL case.

RUN	A-LL-3	A-LL-4	Weight loss percentage of individual gravels per min
	(g)	(g)	(%)
	1757.3	1355.6	4.572 (see **fig.3.12**)
	2198.3	2183.1	0.138
	2108.9	2058.0	0.483
	1787.9	1784.7	0.036
	1328.6	1328.4	0.003
	3053.1	3015.9	0.244
	3012.3	2995.3	0.113
	2736.0	2716.6	0.142
	2595.6	2584.5	0.086
	2329.7	2323.5	0.053
	2007.4	2005.6	0.018
	1903.9	1894.1	0.103
	3500.0	3480.0	0.114
TOTAL	30319.0	29725.3	AVG. = 0.392% (see **fig.3.11**)

Fig.3.12 Granular disintegration from the broken surface (after A–LL–4).

Averages of size distributions of products from andesite and chert were computed by weighting size distributions from each run by duration (**fig. 3.13**). Abrasion that produces sand, silt and clay are referred to as "attrition". Abrasion that produces gravel will be called "breaking". Chert was abraded mainly by breaking and andesite by attrition when L-size gravel particles collided with each other. Chert, because of its brittle nature, was abraded about four times more rapidly than andesite (**Fig. 3.13**).

ii) Detritus produced by abrasion of test gravel

Abrasion products in the 0.5ϕ class just below the test gravel size are referred to as "**gravel 1**"; "**gravel 2**" refers to gravel smaller than **gravel 1**. A part of **gravel 1** might be produced by slight attrition of test gravel.

The ratios of **gravel 2** in the products were higher in chert than andesite for all cases of the same size except LS, and the ratios of sand, silt and clay were higher in andesite in all cases (**fig. 3.14**). This indicates that attrition is dominant in andesite, and breaking is dominant in chert under the experimental conditions of this study.

In terms of the weight percentage of products, which is proportional to the rate of wear of test gravel, andesite was abraded slowly in the LL case and rapidly in MM and SS cases, while chert was abraded very rapidly in the LL case and slowly in MM and SS cases (**fig. 3.14**). The three largest weight percentages of products were in cases A-LS, C-LS and C-LL. All these cases show a high ratio of **gravel 2** in the products. Especially for andesite, **gravel 2** dominates only in the LS case. These facts indicate that the test gravel particles lose weight most effectively by breaking.

3.4.3 Effects of grain size mixture on abrasion

Weight loss percentages are compared between uniform cases and mixed cases in **fig. 3.15**. In LS cases weight loss percentages were calculated for each L and S size. In both andesite and chert, weight losses in S sizes were much higher in LS mixed cases than in SS uniform cases, and weight losses in L sizes were lower in LS cases than in LL cases. This indicates that abrasion products of LS cases are mostly derived from S-size test gravel.

Two processes could explain the effects of size mixture on abrasion (Kodama, 1990a): **i)** crushing of smaller gravels by the impact of larger ones causes higher weight loss percentage of S sizes in LS cases than in SS cases, and **ii)** smaller gravels provide a cushion for larger gravels from the impact of collisions and cause lower weight loss percentage of L sizes in LS cases. LS grain size mixtures produced

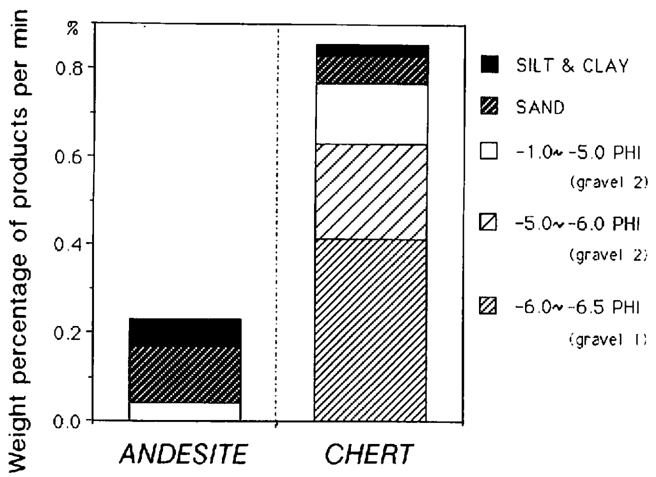


Fig.3.13 Average weight percentage of products and their grain size compositions in L-size uniform cases.

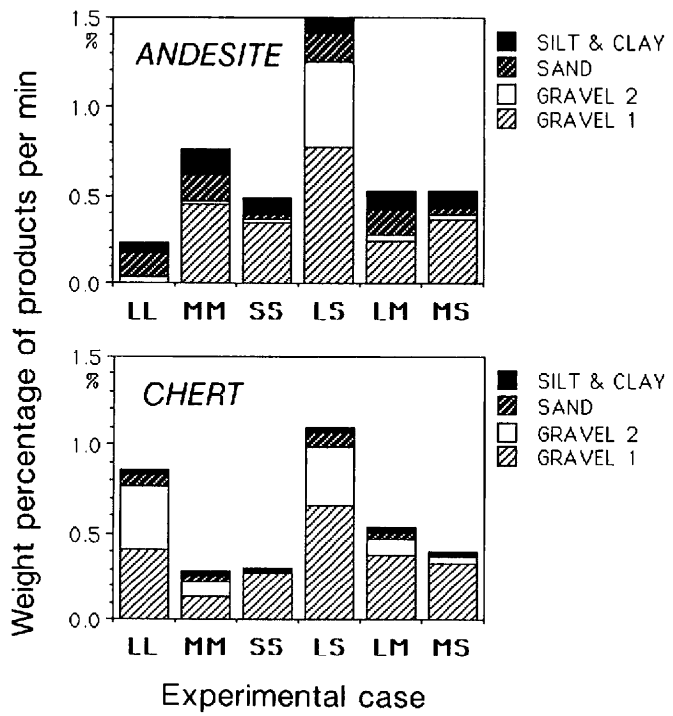


Fig.3.14 Average weight percentage of products and their grain size compositions for all cases.

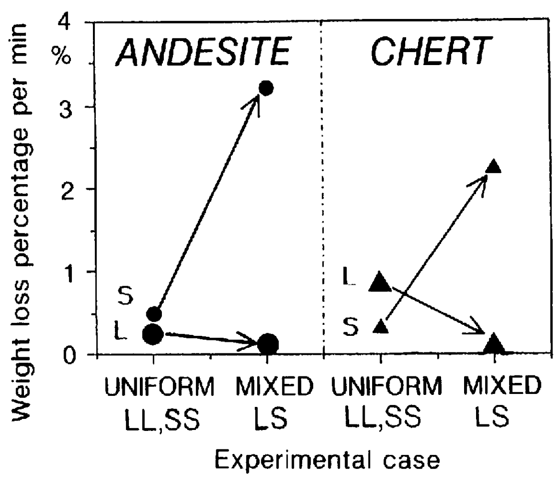


Fig.3.15 The effect of grain size mixture on abrasion rate.

rapid abrasion. This result coincides with Marshall's (1927) conclusion, i.e. when the diameter of the impactor is ten times or more that of the impactee, the impactee will be abraded more rapidly.

It is a very important mechanism of gravel abrasion for different size gravels to interact with one another. Weight loss percentages of S-size gravel in LS cases are as great as 2 to 3%/min (**fig. 3.15**), which is much greater than those (less than 1%/min) in all uniform cases (**fig. 3.14**). Weight loss percentage of S-size gravel in the LS case was about 1%/min higher for andesite than for chert (**fig. 3.15**), while weight loss percentage of L-size gravel in the LL case was lower for andesite than for chert (**fig. 3.13**).

3.4.4 Effects of lithologic mixture on abrasion

From all mixture ratios of the two lithologies, andesite tends to produce fragments of sand, silt and clay, while chert tends to produce gravel (**fig. 3.16**). These results are similar to experiments with single lithologies. In other words, collisions between soft rounded andesite particles with hard sub-rounded chert particles do not affect the resulting size distributions of the fragments.

Figure 3.17 shows the effect of lithologic mixture on weight loss percentage in experiments with L-size uniform material. Andesite shows constant values over a wide range of lithologic mixtures, and chert shows no systematic change resulting from different lithologic mixtures. Weight loss percentages of chert instead depend on the breakage of test gravel into large fragments in repeated experimental runs (C-LL-1, C-LL-4 and A15C05-1, A15C05-3; **tables 3.2 and 3.4**).

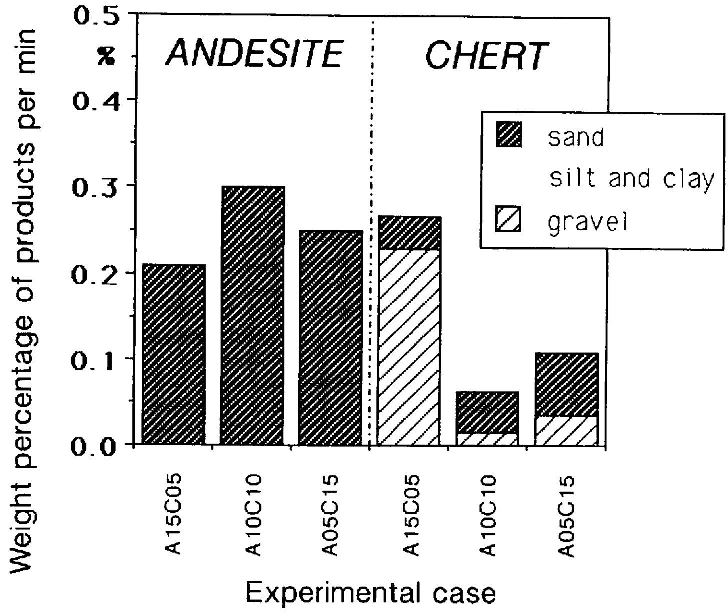


Fig.3.16 Average weight percentage of products and their size composition in the lithologic mixture cases with L-size uniform cobbles.

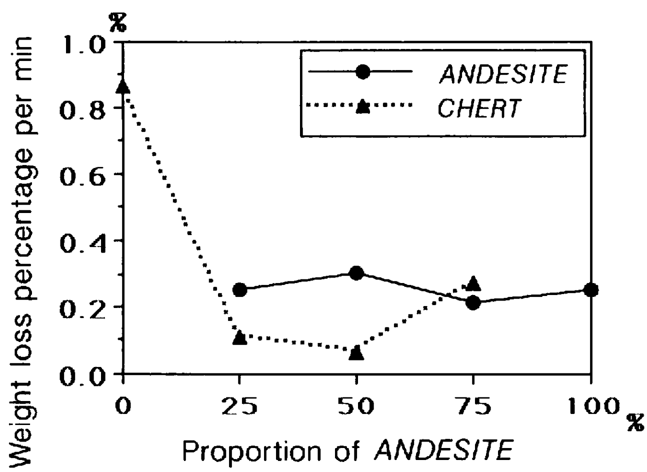


Fig.3.17 Comparison of abrasion rate in L-size uniform cases with different mixtures of lithology.

3.5 Summary

The ERC abrasion mixer experiment (**figs. 3.4～3.7**) was conducted to evaluate the abrasion properties of slightly weathered river-bed gravel. The purpose of this experiment was to simulate the velocity of collision occurring in the Watarase River during a flood (**fig. 3.8**). Test gravels of andesite and chert (**fig. 3.1**) were obtained from the bed of the Watarase. Uniform material of three sizes (L, M, S) and mixtures of two sizes were used (**table 3.1**).

There were five principal results from the experiment. **i)** Test gravels break frequently and decrease in weight rapidly (**table 3.2～3.4**). **ii)** Abrasion of chert produces mostly gravel, while andesite produces mostly sand and silt (**figs. 3.9～3.14**). **iii)** L-size chert cobbles decrease in weight rapidly as a result of being split into smaller gravel pieces, while andesite cobbles break so rarely that their weight decreases very slowly (**fig. 3.13**). **iv)** S-size andesite pebbles decrease in weight more rapidly than chert (**figs. 3.14 and 3.15**). **v)** Size mixture affects abrasion strongly (**fig. 3.15**): smaller fragments are crushed by larger gravel particles and larger gravel decreases its weight loss percentage because small fragments provide a cushion.

CHAPTER IV

DISCUSSION

4.1 Interpretations of the grain size distributions in the Watarase River

4.1.1 Grain size distributions of andesite and chert gravels

Figure 4.1 illustrates contrasting downstream changes of andesite and chert in the bed materials of the Watarase River. The following three points, which correspond to the circled numbers in **fig. 4.1**, can be made. **i)** Andesite particles smaller than -5.5ϕ or -5.0ϕ are very rare in contrast to chert particles which become more abundant downstream. **ii)** There are many andesite particles larger than -7.0ϕ in the upstream part of the study reach but few chert particles in this size. **iii)** The boulders and cobbles of andesite decrease rapidly downstream, but those of chert decrease slowly.

The rarity of andesite pebbles can be attributed to the following results of the ERC abrasion mixer experiment. First, while chert tends to break down to smaller gravel, andesite produces fine particles such as sand and silt (**figs. 3.9~3.14**). This means that when boulders or cobbles are abraded, less M- or S-size gravel is produced from andesite than from chert. Second, M- or S-size gravel of andesite is abraded more rapidly than chert in the uniform case experiments (**fig. 3.14**). Third, small gravel particles are apt to be crushed by large ones, particularly in the LS case experiments. S-size andesite gravel is abraded 1.5 times more rapidly than that of chert (**fig. 3.15**). In contrast, forth, boulders or cobbles of chert tend to break down to pebbles, which are abraded more slowly than andesite pebbles. Therefore chert pebbles become more abundant in river-bed materials downstream.

The lithology of boulders and cobbles is closely related to the material supplied from mountainous areas (Krumbein and Tisdel, 1940; Ichikawa, 1952, 1956). Many andesite boulders are supplied to the river by lahars or debris flows, while the supply of chert boulders to rivers is small, due to the close spacing of joints and bedding planes. Even if chert boulders are supplied to rivers, they are readily broken down downstream by collisions between boulders (according to the extrapolation from the LL case experiments, **fig. 3.13**). This is because the larger the chert gravels are, the more joints and bedding planes they have, and weathering along these discontinuities decreases resistance to impact.

The larger the andesite gravels are, the stronger their resistance to impact becomes. This might be due to the lack of discontinuities in andesite. In fact, broken surfaces of large andesite boulders, which are very difficult to split even with many blows of a geologic hammer, show gray or brown color indicating a lack of weathering.

Results from the ERC abrasion mixer experiment cannot explain fully the difference in the downstream rate of decrease of proportions of boulders or cobbles between andesite and chert. But considering attrition processes that work preferentially on L-size andesite (**fig. 3.13**), large andesite gravels can be abraded *in situ* by sandblasting, or grinding by small particles (**fig. 1.4**). These processes occur not only during severe floods when large gravel particles can be transported, but also during annual floods when they are not transported. In addition, because gravel-bed rivers are usually armoured or paved (e.g., Kellerhals, 1967; Parker, 1982a, 1982b; Andrews and Parker, 1987; Nouh, 1990; Dunkerley, 1990), large andesite gravel particles tend to stay on the surface of bar heads where they are subjected to sandblasting or grinding for a longer time than smaller gravels. On the other hand, large chert gravel under similar conditions is not abraded as much by sandblasting or grinding, and thus does not decrease in diameter rapidly downstream.

Therefore, abrasion properties of andesite and chert in the ERC abrasion mixer experiment can ex-

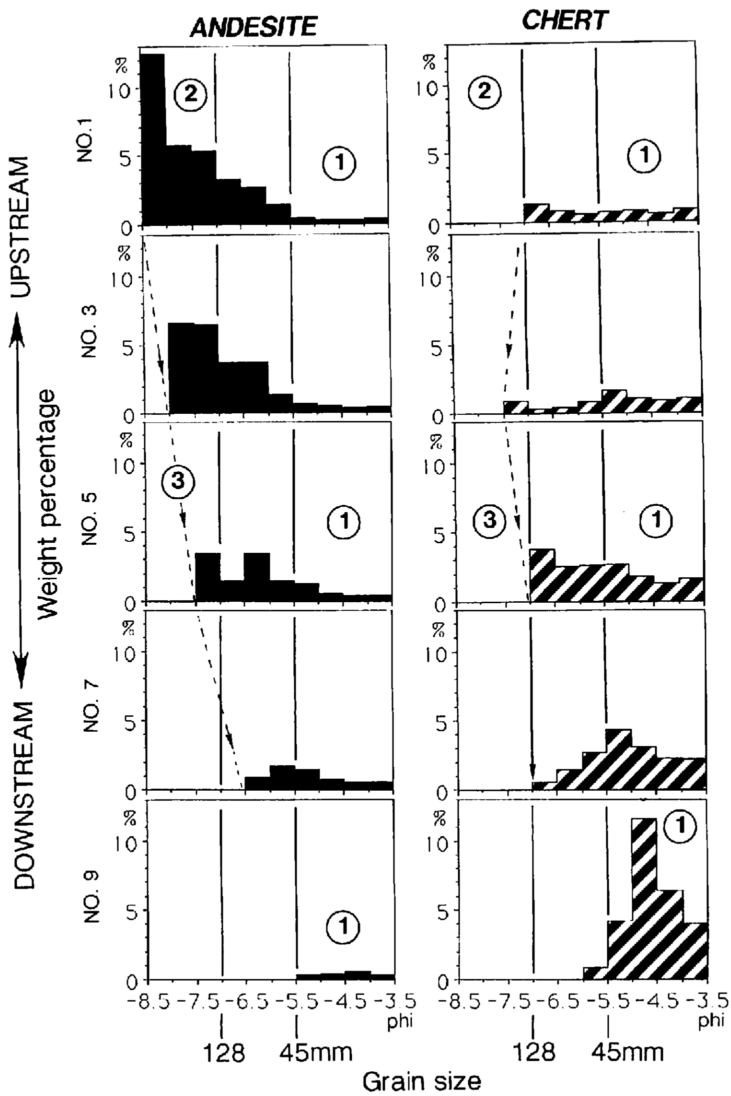


Fig.4.1 Contrasting downstream changes in particle size of andesite and chert in the Watarase River (see text for explanation of circled numbers).

plain qualitatively part of the downstream changes of lithologic composition of gravel in the Watarase River, for which selective transport processes cannot.

4.1.2 Cause of bimodality of river-bed materials

As shown in the Watarase (**fig. 2.5**), size distributions of bed materials in gravel-bed rivers often show bimodality (e.g., Yatsu, 1954b, 1955; Pettijohn, 1957). On the other hand, size distributions of deposits in various sedimentary environments do not show deficiencies of certain sizes (Shea, 1974). Bimodality seems to be one of the characteristics of deposits in rivers under certain conditions. Koide (1952, pp.59-68) and Yatsu (1954c, 1966) proposed the idea of "discontinuity of wearing out of debris" which means "granule sized particles seem to be produced rarely since the pebble has a tendency to be crushed into individual minerals because of its mechanical instability, that is, the pebbles collapse abruptly into sand". Moriyama *et al.* (1980) supported this idea by investigating the grain size distributions both of bed materials in the Yahagi River and of rock-forming minerals and weathering materials of granitic rocks which are widely distributed in the drainage basin of the Yahagi River. Wolcott (1988) pointed out the correlation between geology of a drainage area and size distributions of its bed sediment.

Moss (1972, p.915) postulated that "granules are very likely to be impacted between pebbles or pebbles and bedrock, and then most such particles are both too weak to survive such impacts for long and too immobile in water to escape them. While in the case of small particles, they probably experience many times fewer such impacts than large ones. This is because when moving pebbles collide with each other or with bedrock projections, a stage is reached, just before impact, in which radiating currents are generated from around the destined point of impact between the closing solid surfaces and such currents will tend to remove any small solid objects away from the impact point, then small particles can be more easily moved and rapidly accelerated than large ones".

This study supports part of the idea of Moss (1972). First, in LS cases of the ERC abrasion mixer experiment, it was apparent that S-size gravel particles were crushed by L-size particles and eliminated rapidly (**fig. 3.15**). Second, gravel particles of both lithologies become angular with size reduction (**fig. 4.2**; **appendix V**). In other words, smaller particles have a greater probability of being crushed and cannot avoid breakage long enough to have their corners rounded. These results show that small gravel particles are apt to be crushed. But an issue still remains whether or not medium and fine sand, which comprise the fine mode of the bimodal size distribution of river-bed materials, have a low probability of being crushed.

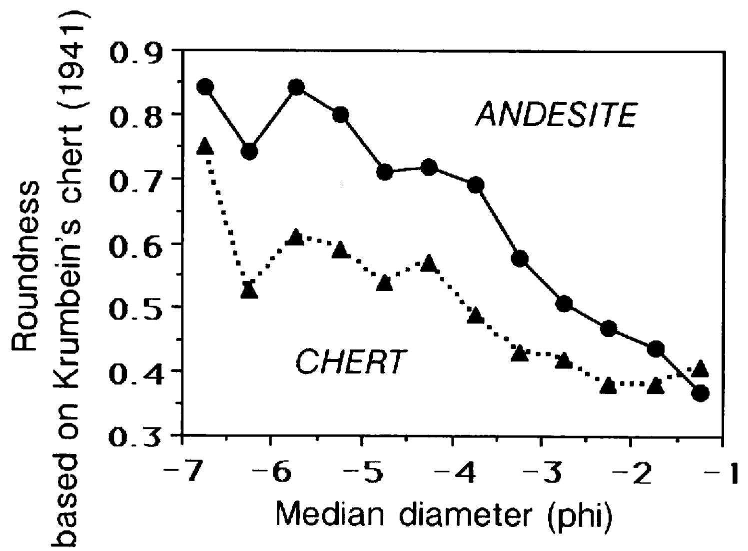


Fig.4.2 Relationship between grain size and roundness from the sample at site No.6 in the Watarase River. Roundness (Krumbein, 1941b) is the average of 30 particles in each size class.

4.1.3 Shape of gravel and grain size reduction

Rounded gravels are thought to be more abraded than angular ones (e.g., Krumbein, 1940, 1941b; Nakayama, 1954; Pearce, 1971). However, if we consider breakage as the dominant cause for reduction of grain size, angularity would indicate a rapid decrease in particle diameter downstream. Chert gravel will be used to explain this phenomenon.

Chert particles have been considered difficult to abrade because their roundness is usually low (e.g., Nakayama and Miura, 1964). As shown in the ERC abrasion mixer experiment, splitting of gravel particles causes their diameter to decrease rapidly while maintaining low values of roundness. In angular gravel, breaking occurs more frequently than attrition, and its decrease in grain size might be more rapid than for rounded gravel.

4.2 Comparison of diminution coefficients obtained from the ERC abrasion mixer experiment with those from previous studies

4.2.1 Calculation of diminution coefficients

Can the results from the ERC abrasion mixer experiment account for downstream fining in natural rivers? This question will be studied by using diminution coefficients. In many gravel-bed rivers, downstream changes in grain size fit an exponential decline of the form proposed by Sternberg (1875):

$$W = W_0 e^{-a_W X} \quad \cdots\cdots (1)$$

where W_0 is the weight of a characteristic particle at an arbitary starting location ($X=0$), W is the characteristic weight at some distance X measured downstream along the river course, and a_W is a coefficient of weight diminution.

The relationship for size diminution (e.g., Krumbein, 1937) is given by :

$$D = D_0 e^{-a_D X} \quad \cdots\cdots (2)$$

in which D is a characteristic linear dimension at some distance X, D_0 is the corresponding dimension at $X=0$, and a_D is a size diminution coefficient which expresses the decreasing rate of grain size downstream. A larger value of a_D means a more rapid decrease in gravel size downstream. Equation (2) follows directly from Equation (1), since $W \propto D^3$ gives

$$3a_D = a_W \quad \cdots\cdots (3)$$

In many cases of the ERC abrasion mixer experiment, the weight of test gravel of each run showed an exponential decline (**fig. A6 - 1**; typical in S-size particles). Thus size diminution coefficients were calculated with equations (1) and (3) from the results of the ERC abrasion mixer experiment in order to compare the values with those of previous experimental studies and those of natural rivers. The initial weight of test gravel particles in each run was used for W_0. W was the weight of gravel particles which remained in the initial size class after each run.

Some method has to be postulated for calculating the equivalent distance of travel in rivers from the duration of abrasion in the ERC abrasion mixer experiment. In previous abrasion mill experiments, equivalent distance X was calculated by the circumference of the drum multiplied by the number of rotations (e.g., Wentworth, 1919; Krumbein, 1941a). But transport distance of gravel particles in a drum does not correspond simply to distance calculated as above, because the mode of movement of a clast among a large amount of gravel in a drum is not simply rolling along the circumference but rather tumbling down with other gravels. In addition, gravel can be dragged up with the rotation of the drum and slip down en masse.

Because no other adequate way for estimating the corresponding travel distance has been proposed, this study uses the same method as previous studies. Travel velocities in all the ERC abrasion mixer experiment equalled about 60m per minute (0.75m × π × 25 rotations per minute). The diminution coefficients, a_D, for each case were calculated with this equivalent distance, W_0 and W **(Tables A6.1, A6.2 and A6.3)**.

One might claim that **gravel 1** (cf. **chapter 3.4.2 ii)**) should also be included in W, because W of previous experiments was usually the weight of all test gravels after the experiment. Gravels in previous experiments abraded gradually to produce fine particles, because of less vigorous abrasion of test gravels. In the ERC abrasion mixer experiment, part of **gravel 1** can be regarded as slightly abraded gravel and might be included in W according to the method of calculation of previous studies. Thus all of **gravel 1** was included in W, which was called W_{G1}. That is, W_{G1} was the weight of gravel particles which remained in the initial size class after each run plus those in the next 0.5ϕ class finer than the initial class (**gravel 1**). Diminution coefficients, a_{DG1}, were also calculated with W_{G1} for reference **(Tables A6.1~A6.3)**.

As the ERC abrasion mixer experiment simulates the collision velocity between saltating particles and bed particles **(fig. 3.8)**, another calculation of equivalent distance can be postulated by assuming that the number of times a particle falls in the ERC abrasion mixer experiment equals the number of saltations of a particle in a river. Thus the equivalent travel distance equals the saltation length times the number of saltations.

An L-size particle was observed to fall from thirty-five to forty times per minute during the ERC abrasion mixer experiment. The saltation length of a particle can be estimated to be thirty times its diameter (e.g., Francis, 1973; Wiberg and Smith, 1985). Thus the maximum estimated equivalent particle velocity equals (forty drops per minute) × (diameter of test gravels) × (thirty); that is about, L: 131m/min, M: 46m/min, S: 16m/min. These results are not that different from the value of 60m per minute, which was calculated according to the method used in previous studies. Therefore there will be little difference between values of diminution coefficients calculated from either equivalent velocity. (Diminution coefficients calculated with this equivalent velocity of L-size particles would show about half and those of S-size would show about four times the diminution coefficient calculated with an equivalent velocity of 60m/sec.)

4.2.2 Comparison of the diminution coefficients with those in previous studies

In the ERC abrasion mixer experiment, diminution coefficients of both andesite and chert are in the range of 10^{-3}~10^{-1}km^{-1} **(figs. 4.3, A6.2)**. In contrast, the diminution coefficients of chert in previous experimental studies were less than 10^{-3}km^{-1} (Kuenen, 1956; Bradley, 1970), and even those for limestone fragments (e.g., Wentworth, 1919; Krumbein, 1941a; Kuenen, 1956) or weathered granite and gneiss (Bradley, 1970) were only 10^{-2}km^{-1} at most. Diminution coefficients obtained from the ERC abrasion mixer experiment are thus greater by one to two orders of magnitude **(fig. 4.3)**.

Diminution coefficients obtained from many Japanese rivers on alluvial fans are from 10^{-2} to 10^{-1} km^{-1} (data source is D_{50} longitudinal variations shown in Yatsu, 1957). These values are consistent with those obtained from the ERC abrasion mixer experiment. The diminution coefficient of the Watarase River, 0.089km^{-1} (cf. **chapter 2.2.1**), is also in this range.

Most recent studies on the cause of downstream fining examine selective transport processes (e.g.,

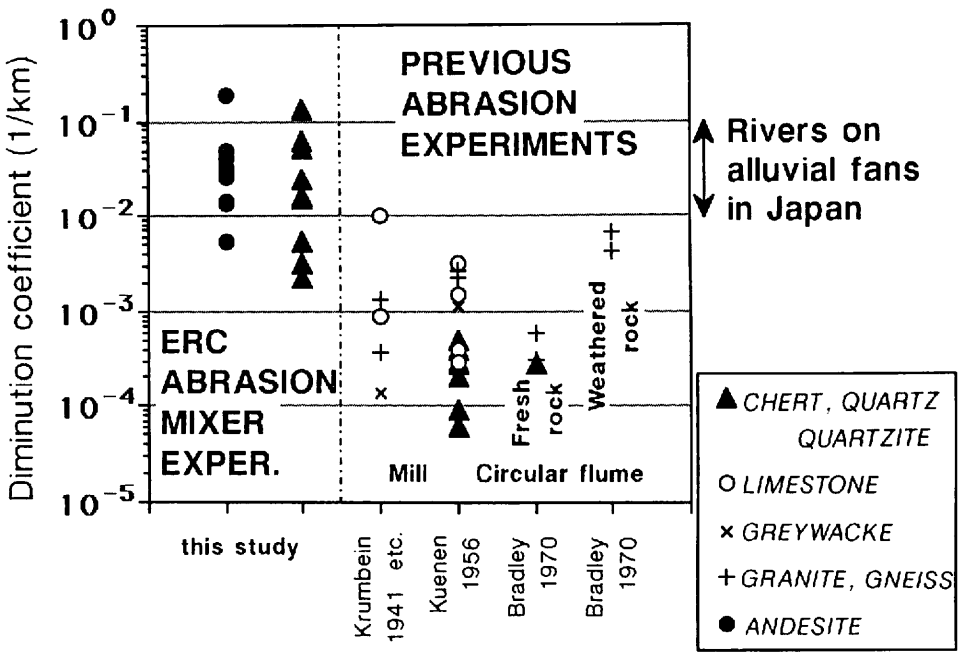


Fig.4.3 Comparison of diminution coefficients obtained from the ERC abrasion mixer experiment with those from previous experimental studies. Diminution coefficients of previous experimental studies and of many Japanese rivers on alluvial fans are after Shaw and Kellerhals (1982, table 12). Diminution coefficients of the ERC abrasion mixer are a_d (column ⑦) in **tables A6.1 ~ A6.3**.

Knighton, 1982; Brierley and Hickin, 1985; Dawson, 1988; Ashworth and Ferguson, 1989). The main reason for this tendency is that the diminution coefficients by previous abrasion experiments are not able to explain those found in natural rivers. But unlike previous experiments, diminution coefficients obtained in the ERC abrasion mixer experiment suggest that abrasion can account for a larger proportion of the downstream decrease in bed material size in rivers.

4.3 Evaluation of abrasion on downstream fining

4.3.1 Argument against Plumley's (1948) discussion

Plumley (1948) investigated longitudinal changes of the lithologic composition of -4.0ϕ to -5.0ϕ sized gravel in terrace deposits of the Black Hills. Figures 15 to 17 in his paper are essentially similar to **fig. 2.10** in **chapter 2.2.2.** He mentioned that "the proportion of chert in the terrace deposits is increasing with distance from the Hills at the expense of all other rock types. In Rapid Creek, the hard rocks (chert, quartz, quartzite) constitute about 40% in the deposits upstream and soft rocks (sandstone, limestone, pre-Cambrian metamorphics) 60%. In the distance of 50km, the hard rocks constitute about 90% of the deposits and the soft rocks 10%." Considering the decrease in median diameter of the terrace deposits with this result, Plumley concluded "selective transport accounts for 75% of the size reduction observed in Rapid Creek and abrasion for the remaining 25%." (Plumley, 1948, p.570). But there must be a mistake in his discussion: using a reduction of 50% in a unit volume made up of both soft and hard rocks.

If chert particles were not abraded at all, soft rocks in Rapid Creek would be abraded to decrease in weight to about 7% of their initial weight in a 50km reach. Moreover, even chert particles must be abraded judging from the results of the ERC abrasion mixer experiment. This means that soft rocks should decrease in weight to less than 7% of their initial weight. In other words, about 93% of the soft rocks in the -4.0ϕ to -5.0ϕ size range seem to be abraded and disappear in the 50km distance along Rapid Creek.

Furthermore, since larger chert gravel particles can be split into smaller particles, the proportion of chert in smaller gravel sizes may increase downstream. It is impossible to evaluate the relative importance of abrasion and sorting on downstream fining in Rapid Creek, because we have no data about the abrasion properties of chert gravel in Rapid Creek and know little about gravel transport during floods in natural rivers.

4.3.2 Evaluation of abrasion on downstream fining in the Watarase River

The results of the ERC abrasion mixer experiment and the grain size reduction of the Watarase River can be related with the following hypothesis in order to estimate the effects of abrasion on downstream fining. The average value of the median diameter of river-bed material in the study reach of the Watarase River is about 35 to 39mm (**fig. 2.6**, **table 2.2**), namely the M-size class (-5.0ϕ to -5.5ϕ). It is assumed that the loss of M-size gravel by abrasion represents an average loss for the entire range of sizes (a similar argument as made by Plumley, 1948, p.570–571). Furthermore, we can neglect selective transport by lithology within such a restricted range of size.

From the results of the ERC abrasion mixer experiment, the arithmetic mean of the diminution coefficients of the M-size chert gravel is about 0.033km^{-1} (C-MM: 0.01555km^{-1}, C-LM: 0.0.06029km^{-1}, C-MS: 0.02358km^{-1}). M-size chert diameter, D_0, at No.1 in the Watarase River is expected to decrease to $0.52D_0$ at No.9, which is about 20km downstream from No.1, because the diameter D at No.9 is expressed as follows:

$$D = D_0 e^{-0.033 \times 20}$$

This decrease in diameter is supposed to equal the ratio between the completely diminished gravels by abrasion and unchanged gravels. According to this hypothesis, the number of M-size chert gravel particles decreases to 52% from site No.1 to site No.9.

The proportion of M-size chert gravel in the Watarase increases from 10.5% to 54.8% from site No.1 to site No.9. However, the ERC abrasion mixer experiment indicates that even chert is eliminated downstream. Of 10,000 andesite and chert particles of M-size at site No.1, 1,050 are chert. Considering our measured rates of chert abrasion, 52% (about 546) of these remain in this size when they reach site No.9. The number of M-size particles of other lithologies would be 8,950 at site No.1 and 450 at site No.9. Thus the total number of M-size particles would decrease by abrasion from 10,000 (site No.1) to 996 (site No.9). This means that 90% of the bed load would be lost from site No.1 to site No.9 by abrasion alone. Thus the median diameter would be expected to decrease by such a large percentage. In fact, median diameter decreases from 66mm (site No.1) to 10.5mm (site No.9) (**table 2.2**), or about 84%, which suggests that abrasion alone may account for downstream fining.

4.3.3 Argument against discussions of Bradley *et al.* (1972) and Dawson(1988)

These conclusions differ from those of Bradley *et al.* (1972) and Dawson (1988), who concluded that abrasion accounts for less than 10% of downstream fining. The experimental method of Bradley *et al.* (1972) did not adequately replicate particle-to-particle collisions. Regarding Dawson (1988), it is not valid to compare grain size data obtained from an aggrading tributary situated on the upper part of the drainage area with data from degrading rivers (Shaw and Kellerhals's data; 1982) situated on the lower part of several drainage basins. Dawson (1988) uses Shaw and Kellerhals's (1982) data from several drainage basins (e.g., the Athabasca River, the North Saskatchewan River) to produce an average diminution coefficient of degrading rivers. He compares this with the diminution coefficient of a relatively small tributary (the Sunwapta River).

Three previous studies which evaluate the relative importance of abrasion and sorting on downstream fining appear to be flawed. A closer examination of the data leads to a conclusion that abrasion is a more important process in downstream fining.

4.4 Abrasion as an important process in producing suspended sediments

Suspension in rivers has been attributed to different sources (Richards, 1982, pp.47–49). Wash load, which is usually recognized by its distinctive size properties, is derived from areas outside of the channel system such as from soil erosion of slopes, while suspended sediment is delivered from channel perimeters such as fine sediment trapped in pores between coarser bed material, which is very low in a gravel bed river (Lambert and Walling, 1988), and river bank collapse (e.g., Carson *et al.*, 1973; Garrad and Hey, 1989). From the results of the ERC abrasion mixer experiment, another possible source for the suspended sediment —— abrasion of bed materials during transport of gravel —— can be proposed. This process has been examined very little (Kennedy and Arikan, 1990; Mizuyama, 1990).

The ERC abrasion mixer experiment illustrates that abrasion of gravel produces a great amount of sand and silt which can become part of the suspended load during a flood. In other words, part of the bedload can be altered to the suspended load. This may be significant for interpreting sediment budgets in a drainage basin. Such a concept has not been considered in previous studies on the longitudinal profile of a river (e.g., Shulits, 1941) but should be in the future.

CHAPTER V

CONCLUSIONS

This study demonstrated that a downstream reduction of size of river-bed gravel in an alluvial fan can be explained by the processes of abrasion associated with particle to particle collisions during floods. Longitudinal grain-size reduction and some characteristics in lithologic composition of the river-bed material in the Watarase River can be explained by the results of the ERC abrasion mixer experiment.

Lithologic composition of river-bed materials of all grain sizes change downstream in the Watarase. The proportion of chert increases downstream in all size classes of gravel larger than -3.5ϕ. Since the mobility of gravel depends mainly on its size, hydraulic sorting by lithology does not occur within the same size class. Therefore longitudinal changes in gravel lithology must be explained by abrasion.

Besides, the size distribution of gravel in the Watarase is strongly related to lithology. Andesite boulders and large cobbles make up the framework sizes in the upstream part, while in the downstream part, chert pebbles make up the framework. These phenomena are related to their abrasion properties, which were illustrated by the results of the ERC abrasion mixer experiment (laboratory study on abrasion). Large gravel particles of chert tend to decrease their weight rapidly by being split into smaller gravels, while large andesite particles decrease their weight slowly because they are rarely split but instead are abraded to yield fine fragments such as sand and silt. This might cause the dominance in andesite boulders and cobbles in the upstream part of the Watarase River. Andesite pebbles decrease their weight more rapidly than those of chert, and fewer andesite than chert pebbles are yielded by splitting of boulders or cobbles. These properties may cause the dominance of chert pebbles in the downstream part of the Watarase River.

In the ERC abrasion mixer experiment, diminution coefficients of both andesite and chert are in the range of $10^{-3}\sim10^{-1}$ (**fig. 4.3**) and are larger by one to two orders of magnitude than those from previous experiments on abrasion. This resulted mainly because the ERC abrasion mixer experiment closely simulated particle-particle collisions during floods in the Watarase River. No previous experimental studies on gravel abrasion have been conducted under such vigorous conditions.

Previous abrasion experiments indicate that abrasion is a minor factor in the process of downstream fining, particularly in rivers on alluvial fans. Yet diminution coefficients obtained from the ERC abrasion mixer experiment are consistent with those obtained from many Japanese rivers on alluvial fans ($10^{-2}\sim10^{-1}$), which includes the diminution coefficient of the Watarase River, 0.089 (km^{-1}). This result shows that the diminution coefficients in rivers on alluvial fans in Japan can be explained by abrasion alone.

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APPENDIX I

Rate of broken round in the river-bed gravel

Table A1.1 Shape of andesite gravel in the Azusa River.

Sampling site: 1.5km downstream from the Niibuchi-bridge at Shimashima

Gravel size	Total number	Gravel shape Number and percentage of gravel particles classified to		
		Broken round	Transition	Rounded gravel
−3 ～ −4φ	——	——		——
−4 ～ −5φ	23	10 (43.5%)	10 (43.5%)	3 (13.0%)
−5 ～ −6φ	46	15 (32.6%)	18 (39.1%)	13 (28.3%)
−6 ～ −7φ	67	13 (19.4%)	28 (41.8%)	26 (38.8%)
−7 ～ −8φ	64	13 (20.3%)	30 (46.9%)	21 (32.8%)
−8 ～ −9φ	52	7 (13.5%)	31 (59.6%)	14 (26.9%)
SUM	252	58 (23.0%)	117 (46.4%)	194 (30.6%)

Sampling site: 8.9km downstream from the Niibuchi-bridge at Shimashima

Gravel size	Total number	Gravel shape Number and percentage of gravel particles classified to		
		Broken round	Transition	Rounded gravel
−3 ～ −4φ	——		——	——
−4 ～ −5φ	5	3 (60.0%)	1 (20.0%)	1 (20.0%)
−5 ～ −6φ	58	12 (20.7%)	35 (60.3%)	11 (19.0%)
−6 ～ −7φ	69	12 (17.4%)	34 (49.3%)	23 (33.3%)
−7 ～ −8φ	69	17 (24.6%)	20 (29.0%)	32 (46.4%)
−8 ～ −9φ	51	5 (9.8%)	22 (43.1%)	24 (47.1%)
SUM	252	49 (19.4%)	112 (44.4%)	203 (36.1%)

Sampling site: 12.5km downstream from the Niibuchi-bridge at Shimashima

Gravel size	Total number	Gravel shape Number and percentage of gravel particles classified to		
		Broken round	Transition	Rounded gravel
−3 ～ −4φ		——	——	
−4 ～ −5φ	34	10 (29.4%)	15 (44.1%)	9 (26.5%)
−5 ～ −6φ	76	27 (35.5%)	33 (43.4%)	16 (21.1%)
−6 ～ −7φ	73	22 (30.1%)	32 (43.8%)	19 (26.0%)
−7 ～ −8φ	54	12 (22.2%)	19 (35.2%)	23 (42.6%)
−8 ～ −9φ	3	1 (33.3%)	1 (33.3%)	1 (33.3%)
SUM	240	72 (30.0%)	100 (41.7%)	168 (28.3%)

Table A1.2 Shape of andesite gravel in the Sagae River.

Sampling site: 1.75km downstream from confluence of the Yuuno River

Gravel size	Total number	Gravel shape Number and percentage of gravel particles classified to		
		Broken round	Transition	Rounded gravel
−3 ～ −4φ	5	1 (20.0%)	1 (20.0%)	3 (60.0%)
−4 ～ −5φ	32	6 (18.8%)	10 (31.3%)	16 (50.0%)
−5 ～ −6φ	66	23 (34.8%)	17 (25.8%)	26 (39.4%)
−6 ～ −7φ	58	25 (43.1%)	17 (29.3%)	16 (27.6%)
−7 ～ −8φ	22	6 (27.3%)	12 (54.5%)	4 (18.2%)
−8 ～ −9φ	1	0 (0.0%)	1(100.0%)	0 (0.0%)
SUM	184	61 (33.2%)	58 (31.5%)	65 (35.3%)

Sampling site: 4.0km downstream from confluence of the Yuuno River

Gravel size	Total number	Gravel shape Number and percentage of gravel particles classified to		
		Broken round	Transition	Rounded gravel
−3 ～ −4φ	9	1 (11.1%)	3 (33.3%)	5 (55.6%)
−4 ～ −5φ	45	7 (15.6%)	21 (46.7%)	17 (37.8%)
−5 ～ −6φ	76	10 (13.2%)	31 (40.8%)	35 (46.1%)
−6 ～ −7φ	55	15 (27.3%)	24 (43.6%)	16 (29.1%)
−7 ～ −8φ	54	10 (18.5%)	32 (59.3%)	12 (22.2%)
−8 ～ −9φ	1	0 (0.0%)	1(100.0%)	0 (0.0%)
SUM	240	43 (17.9%)	112 (46.7%)	85 (35.4%)

Sampling site: 9.8km downstream from confluence of the Yuuno River

Gravel size	Total number	Gravel shape Number and percentage of gravel particles classified to		
		Broken round	Transition	Rounded gravel
−3 ～ −4φ	9	4 (44.4%)	3 (33.3%)	2 (22.2%)
−4 ～ −5φ	61	15 (24.6%)	22 (36.1%)	24 (39.3%)
−5 ～ −6φ	105	13 (12.4%)	46 (43.8%)	46 (43.8%)
−6 ～ −7φ	58	13 (22.4%)	25 (43.1%)	20 (34.5%)
−7 ～ −8φ	54	15 (27.8%)	27 (50.0%)	12 (22.2%)
−8 ～ −9φ	54	12 (22.2%)	39 (72.2%)	3 (5.6%)
SUM	341	72 (21.1%)	162 (47.5%)	107 (31.4%)

APPENDIX II

Mean river-bed elevations along the lower course of the Watarase River

Table A2 Mean bed elevations along the lower Watarase River at 1983 and calculated mean slope.

Downstream distance from Kiryu (km)	River-bed elevation (m)	Slope averaged over 2.0 ~ 2.5km (× 1/1000)	Downstream distance from Kiryu (km)	River-bed elevation (m)	Slope averaged over 2.0 ~ 2.5km (× 1/1000)
0.00	107.548		8.20	53.041	4.54
0.20	104.232		8.40	53.938	4.15
0.40	104.410		8.60	52.553	4.39
0.60	102.640		8.80	52.019	3.52
0.80	100.394		9.00	50.763	4.36
1.00	99.772	7.40	9.20	49.704	3.37
1.20	99.198	6.34	9.40	48.659	4.30
1.40	96.440	7.11	9.60	48.205	3.78
1.60	95.306	7.10	9.80	47.668	3.73
1.80	93.312	6.65	10.00	46.630	3.40
2.00	92.740	7.10	10.20	46.295	5.42
2.20	91.542	7.42	10.40	45.340	3.00
2.40	90.189	7.10	10.60	44.990	3.32
2.60	88.438	7.13	10.80	44.562	3.58
2.80	87.104	7.31	11.00	43.957	3.05
3.00	85.582	6.93	11.20	38.864	3.20
3.20	84.353	7.32	11.40	42.653	2.99
3.40	82.241	6.82	11.60	41.568	2.94
3.60	81.037	7.26	11.80	40.499	3.43
3.80	78.697	6.73	12.00	40.540	3.52
4.00	78.871	7.37	12.20	39.901	1.13
4.20	76.904	6.62	12.40	39.370	3.70
4.40	76.547	6.30	12.60	39.111	3.58
4.60	73.909	6.52	12.80	37.703	2.95
4.80	73.644	5.98	13.00	36.923	3.11
5.00	70.841	6.55	13.20	36.607	2.94
5.20	71.107	6.26	13.40	35.260	3.15
5.40	69.641	5.40	13.60	34.417	3.27
5.60	68.000	5.27	13.80	34.593	2.68
5.80	66.744	6.24	14.00	34.320	2.60
6.00	65.778	5.60	14.20	34.012	2.68
6.20	64.382	6.16	14.40	33.066	2.15
6.40	65.750	6.34	14.60	32.564	1.84
6.60	63.376	5.51	14.80	32.342	2.19
6.80	61.161	6.02	15.00	31.728	2.36
7.00	59.648	5.21	15.20	31.247	2.59
7.20	58.788	5.67	15.40	30.959	2.52
7.40	56.953	5.91	15.60	30.743	2.09
7.60	56.981	5.41	15.80	30.221	2.99
7.80	54.699	4.57	16.00	29.594	2.83
8.00	55.355	4.44	16.20	28.833	3.06

Table A2 (continued)

Downstream distance from Kiryu (km)	River-bed elevation (m)	Slope averaged over 2.0 ~ 2.5km (× 1/1000)	Downstream distance from Kiryu (km)	River-bed elevation (m)	Slope averaged over 2.0 ~ 2.5km (× 1/1000)
16.40	28.031	3.06	26.25	18.458	0.74
16.50	28.598	3.09	26.50	18.083	0.95
16.70	26.665	1.57	26.75	17.546	0.64
16.90	26.342	1.32	27.00	18.223	0.94
17.00	25.745	1.28	27.25	17.775	1.09
17.10	25.764	0.99	27.50	17.881	1.24
17.25	25.642	1.40	27.75	17.028	0.87
17.50	27.552	0.48	28.00	17.137	0.58
17.75	27.283	0.30	28.25	16.613	1.04
18.00	26.536	0.27	28.50	16.484	1.02
18.25	26.193	0.43	28.75	15.355	1.13
18.50	25.803	0.29	29.00	15.900	0.67
18.75	25.684	1.21	29.25	16.092	0.28
19.00	25.702	1.33	29.50	15.624	0.70
19.25	25.128	1.22	29.75	15.218	0.71
19.50	24.721	1.36	30.00	15.048	0.33
19.75	24.916	1.15	30.25	15.362	0.28
20.00	24.516	1.10	30.50	16.448	0.76
20.25	23.968	1.32	30.75	14.871	0.27
20.50	23.474	1.44	31.00	14.702	0.25
20.75	22.785	1.17	31.25	14.525	−0.04
21.00	22.924	1.66	31.50	15.188	0.18
21.25	22.928	1.24	31.75	14.194	0.48
21.50	22.393	1.20	32.00	14.961	0.19
21.75	21.532	1.10	32.25	14.583	0.09
22.00	21.803	1.06	32.50	15.147	0.22
22.25	20.754	1.13	32.75	14.900	−0.13
22.50	21.426	1.29	33.00	15.249	−0.41
22.75	20.959	1.03	33.25	14.400	0.28
23.00	20.719	0.83	33.50	14.481	−0.02
23.25	20.137	0.95	33.75	13.963	0.28
23.50	20.090	0.63	34.00	15.504	0.34
23.75	19.707	0.68	34.25	15.220	0.73
24.00	19.814	0.62	34.50	14.252	0.49
24.25	19.452	0.79	34.75	14.640	0.61
24.50	19.429	0.47	35.00	14.445	0.69
24.75	19.189	0.35	35.25	14.044	1.29
25.00	19.734	0.50	35.50	13.420	
25.25	19.397	0.69	35.75	13.183	
25.50	18.734	0.76	36.00	12.948	
25.75	18.967	0.48	36.25	12.237	
26.00	19.213	0.57	36.50	12.284	

Mean elevations were measured by the Watarase River Work Office, Kanto Regional Construction Bureau, the Ministry of Construction.

APPENDIX III

Compressive strength of the test gravel particles used in the ERC abrasion mixer experiment

Table A3.1 Compressive strength of the L-size andesite gravels.

No.	Weight (g)	Immersed weight (g)	Volume (cm³)	P (kg)	Sc (kg/cm²)
1	2309	1351	958	2738	148.3
2	1927	1179	748	4845	309.5
3	1667	1023	644	2435	171.9
4	1496	900	596	4377	325.3
5	1905	1107	798	4644	284.1
6	1443	870	573	2770	211.3
7	1465	822	643	4130	291.8
8	1484	870	614	3013	219.5
9	1825	1088	737	3512	226.5
10	2250	1372	878	3770	216.4
11	1592	984	608	3932	288.4
12	1175	690	485	3526	300.6
13	1565	939	626	4130	297.0
14	1437	856	581	5028	380.1
15	1487	888	599	2033	150.6
16	2737	1590	1147	3592	172.5
17	2077	1228	849	3265	191.7
18	1638	991	647	4213	296.4
19	2063	1261	802	4597	280.3
20	1482	908	574	5500	419.1
21	1206	711	495	1815	152.7
22	1674	1068	606	4965	364.9
23	1435	857	578	5332	404.4
24	1868	1148	720	3212	210.4
25	1366	769	597	3930	291.7
26	2425	1494	931	5675	313.3
27	1867	1159	708	3555	235.5
28	1324	803	521	3255	264.6
29	2026	1220	806	4390	266.8
30	1627	919	708	4558	302.0
31	1667	992	675	3303	225.9
32	1337	793	544	1500	118.5
33	1597	937	660	2200	152.7
34	1541	893	648	2208	155.2
35	1662	981	681	4318	293.6
36	1714	1053	661	2367	164.2
37	1829	1113	716	3190	209.8
38	2392	1391	1001	1208	63.5
39	2033	1268	765	325	20.4
40	1199	717	482	4242	363.2
41	1393	819	574	3038	231.5
42	2077	1281	796	1360	83.3
43	1398	815	583	4357	328.6
44	2350	1359	991	5160	273.2
45	1908	1204	704	3248	216.0
46	1553	800	753	4473	284.4
47	1233	729	504	3700	307.5
48	1312	749	563	2850	220.0
49	1244	762	482	3555	304.4
50	1325	777	548	4278	336.2
51	2278	1380	898	4060	229.6
52	1293	746	547	2875	226.2
Average	1696	1012	684	3549	246.1

Table A3.2 Compressive strength of the M-size andesite gravels.

No.	Weight (g)	Immersed weight (g)	Volume (cm^3)	P (kg)	Sc (kg/cm^2)
1	121.43	73.78	47.65	1502	601.5
2	96.68	60.23	36.45	1740	833.0
3	94.04	54.92	39.12	643	293.7
4	83.22	50.05	33.17	885	451.2
5	127.38	79.89	47.49	1711	686.7
6	96.28	57.29	38.99	818	374.4
7	92.74	56.32	36.42	560	268.3
8	127.97	76.51	51.46	668	254.1
9	146.92	86.45	60.47	958	327.3
10	116.88	73.50	43.38	1087	463.4
11	77.51	49.08	28.43	1226	692.7
12	117.18	72.60	44.58	1180	494.0
13	83.74	51.50	32.24	991	514.9
14	51.80	30.84	20.96	412	285.2
15	104.45	64.60	39.85	466	210.2
16	85.25	50.35	34.90	478	235.6
17	107.23	66.02	41.21	1085	478.6
18	55.11	28.59	26.52	389	230.2
19	107.33	65.29	42.04	1153	501.9
20	138.20	88.39	49.81	3593	1396.9
21	119.64	74.91	44.73	1816	758.5
22	109.23	64.42	44.81	896	373.8
23	109.98	67.70	42.28	1684	730.3
24	121.57	75.17	46.40	861	350.9
25	85.87	52.57	33.30	500	254.2
26	69.92	41.38	28.54	519	292.5
27	99.97	57.57	42.40	318	137.6
28	127.43	79.82	47.61	786	314.9
29	67.28	39.21	28.07	750	427.4
30	135.48	79.94	55.54	526	190.2
31	75.36	44.04	31.32	386	204.5
32	79.39	45.02	34.37	561	279.3
33	69.79	40.47	29.32	363	200.9
34	79.88	46.24	33.64	1026	518.2
35	66.36	42.05	24.31	930	583.3
36	70.94	44.36	26.58	1249	738.1
37	61.51	37.55	23.96	699	442.7
38	55.61	34.31	21.30	700	479.5
39	70.98	44.19	26.79	1637	962.3
40	47.31	27.46	19.85	94	67.5
41	56.71	35.42	21.29	978	670.1
42	136.82	86.92	49.90	1803	700.1
43	74.08	48.05	26.03	425	254.7
44	95.81	55.24	40.57	380	169.4
45	110.84	64.51	46.33	655	267.2
46	80.63	49.91	30.72	1364	731.9
47	138.91	83.63	55.28	394	142.9
48	51.24	29.68	21.56	242	164.4
49	95.57	58.53	37.04	1280	606.3
50	72.54	44.12	28.42	1575	890.1
51	66.48	40.59	25.89	692	416.2
52	84.01	51.26	32.75	1702	875.1
Average	92.66	56.20	36.46	949	457.5

Table A3.3 Compressive strength of the S-size andesite gravels.

No.	Weight (g)	Immersed weight (g)	Volume (cm^3)	*P* (kg)	*Sc* (kg/cm^2)
1	8.42	5.20	3.22	542	1308.2
2	5.16	3.13	2.03	71	233.1
3	5.47	3.29	2.18	148	463.3
4	5.27	3.28	1.99	255	848.3
5	4.27	2.68	1.59	103	397.9
6	4.16	2.38	1.78	21	75.3
7	6.22	3.91	2.31	156	469.9
8	5.80	3.56	2.24	418	1285.1
9	4.52	2.63	1.89	202	695.5
10	5.10	3.05	2.05	125	407.7
11	5.60	3.54	2.06	78	253.6
12	6.78	4.10	2.68	164	447.4
13	5.78	3.53	2.25	312	956.3
14	4.16	2.62	1.54	185	730.1
15	7.18	4.13	3.05	413	1033.5
16	4.33	2.62	1.71	292	1074.7
17	3.89	2.37	1.52	82	326.5
18	2.47	1.44	1.03	68	350.9
19	2.84	1.68	1.16	164	781.8
20	2.15	1.22	0.93	120	662.9
21	5.87	3.42	2.45	193	558.9
22	6.23	3.81	2.42	186	543.1
23	4.51	2.71	1.80	152	540.6
24	3.94	2.19	1.75	106	384.2
25	5.37	3.34	2.03	301	988.1
26	6.94	4.05	2.89	263	682.2
27	5.73	3.63	2.10	225	722.1
28	4.73	2.98	1.75	281	1018.4
29	5.35	3.38	1.97	529	1771.7
30	3.12	2.09	1.03	77	397.4
31	5.34	2.85	2.49	92	263.6
32	5.42	3.08	2.34	114	340.4
33	6.81	4.08	2.73	306	824.5
34	7.29	4.39	2.90	304	786.8
35	6.83	4.30	2.53	378	1071.5
36	6.68	3.86	2.82	596	1571.5
37	4.05	2.25	1.80	41	145.8
38	5.42	3.21	2.21	194	601.8
39	4.67	2.84	1.83	134	471.4
40	3.81	2.23	1.58	105	407.4
41	5.31	2.94	2.37	125	370.1
42	5.95	3.60	2.35	206	613.4
43	5.81	3.42	2.39	353	1039.3
44	4.56	2.71	1.85	144	502.9
45	4.81	2.85	1.96	192	645.2
46	3.81	2.05	1.76	195	704.1
47	3.69	2.07	1.62	80	305.3
48	3.35	1.96	1.39	75	316.9
49	5.59	3.30	2.29	554	1678.3
50	3.16	1.91	1.25	39	176.9
51	4.66	2.74	1.92	195	664.4
52	4.90	2.89	2.01	494	1632.5
Average	5.06	3.03	2.03	214	683.5

Table A3.4 Compressive strength of the L-size andesite gravels.

No.	Weight (g)	Immersed weight (g)	Volume (cm^3)	*P* (kg)	Sc (kg/cm^2)
1	1769	1103	666	9030	623.2
2	1882	1175	707	7820	518.6
3	1565	973	592	6530	487.5
4	1785	1110	675	6050	413.8
5	2319	1432	887	3850	219.5
6	1255	780	475	2880	249.0
7	2007	1249	758	7075	447.9
8	1637	1019	618	4362	316.4
9	1278	793	485	4945	421.6
10	1570	979	591	4700	351.3
11	1937	1197	740	4865	313.0
12	1487	922	565	4960	382.0
13	1191	740	451	4725	422.9
14	1876	1168	708	2160	143.1
15	1195	741	454	5040	449.1
16	1721	1069	652	8167	571.7
17	1452	898	554	6020	469.7
18	1442	895	547	2460	193.6
19	1933	1190	743	5020	322.1
20	2117	1313	804	9450	575.2
21	1838	1142	696	2993	200.6
22	2055	1276	779	7800	484.9
23	1514	935	579	4775	361.8
24	1515	944	571	5500	420.6
25	2202	1373	829	4778	285.0
26	1998	1243	755	8075	512.6
27	1397	860	537	2010	160.1
28	1410	878	532	4715	378.0
29	1632	1013	619	3000	217.4
30	1299	807	492	7150	603.8
31	2003	1249	754	7418	471.3
32	2149	1333	816	3964	238.9
33	2164	1335	829	3080	183.7
34	1574	979	595	8230	612.3
35	1415	881	534	3500	279.9
36	1645	1015	630	3000	214.9
37	2233	1389	844	5440	320.6
38	1466	905	561	7376	570.7
39	1264	788	476	5407	466.8
40	1841	1143	698	5870	392.6
41	2247	1402	845	3746	220.6
42	3337	2075	1262	4520	203.7
43	1779	1114	665	5890	406.9
44	1725	1073	652	2075	145.2
45	2755	1717	1038	5110	262.3
46	2184	1368	816	3355	202.2
47	2065	1287	778	6910	429.9
48	1966	1222	744	5880	376.9
49	2235	1392	843	6735	397.2
50	1762	1091	671	3645	250.3
51	2279	1424	855	4615	269.6
52	2346	1475	871	9030	521.1
Average	1821	1132	689	5302	364.5

Table A3.5 Compressive strength of the M-size chert gravels.

No.	Weight (g)	Immersed weight (g)	Volume (cm^3)	P (kg)	Sc (kg/cm^2)
1	199.60	122.51	77.09	1756	510.2
2	84.07	51.44	32.63	1655	853.0
3	85.88	52.09	33.79	512	257.8
4	64.90	40.00	24.90	968	597.5
5	48.64	29.33	19.31	505	369.3
6	96.61	58.99	37.62	2415	1132.1
7	67.69	41.30	26.39	1185	703.6
8	92.97	57.17	35.80	1337	647.8
9	62.36	38.80	23.56	964	617.4
10	83.80	51.74	32.06	1087	566.9
11	124.91	78.06	46.85	4153	1681.9
12	95.30	59.21	36.09	2035	980.7
13	54.34	33.06	21.28	800	548.3
14	66.15	41.32	24.83	2655	1641.8
15	119.31	73.77	45.54	1723	711.1
16	65.85	40.12	25.73	1965	1186.6
17	76.59	46.92	29.67	1310	719.4
18	120.40	74.71	45.69	1750	720.7
19	118.93	72.65	46.28	2025	826.8
20	65.30	39.37	25.93	895	537.7
21	147.02	90.68	56.34	1385	496.0
22	79.23	47.98	31.25	1285	681.7
23	71.84	42.91	28.93	1275	712.1
24	40.37	24.74	15.63	1448	1219.1
25	63.75	38.70	25.05	1170	719.3
26	53.20	30.12	23.08	1843	1196.6
27	58.52	35.74	22.78	1218	797.7
28	66.67	40.28	26.39	456	270.8
29	66.29	40.19	26.10	1280	765.6
30	47.62	28.72	18.90	1290	956.9
31	85.12	51.97	33.15	1545	788.0
32	64.07	38.90	25.17	1644	1007.5
33	78.01	48.21	29.80	3480	1905.5
34	48.34	29.51	18.83	450	334.6
35	139.94	86.22	53.72	1500	554.5
36	54.02	32.55	21.47	450	306.6
37	144.30	89.16	55.14	875	317.9
38	93.64	58.31	35.33	1950	953.2
39	110.18	67.62	42.56	2010	867.8
40	75.37	46.07	29.30	1800	996.8
41	55.95	34.30	21.65	1160	786.0
42	50.55	30.72	19.83	1505	1081.2
43	56.05	32.86	23.19	1507	975.3
44	66.98	40.13	26.85	942	552.9
45	62.32	36.87	25.45	1180	717.8
46	66.83	40.79	26.04	735	440.3
47	69.47	41.23	28.24	1700	964.8
48	83.79	51.20	32.59	1510	778.9
49	72.30	43.12	29.18	1164	646.4
50	96.49	58.67	37.82	1890	882.9
51	128.30	80.52	47.78	2560	1023.3
52	122.81	79.21	43.60	3386	1438.6
Average	82.94	50.78	32.16	1525	806.7

Table A3.6 Compressive strength of the S-size chert gravels.

No.	Weight (g)	Immersed weight (g)	Volume (cm^3)	*P* (kg)	*Sc* (kg/cm^2)
1	7.63	4.50	3.13	490	1205.3
2	8.11	5.13	2.98	694	1763.9
3	10.40	6.46	3.94	668	1409.4
4	8.99	5.60	3.39	389	907.3
5	6.98	4.30	2.68	288	785.6
6	6.78	4.24	2.54	508	1436.2
7	6.28	3.91	2.37	769	2276.9
8	7.09	4.41	2.68	670	1827.7
9	6.33	3.90	2.43	470	1368.6
10	7.00	4.50	2.50	323	922.9
11	6.55	4.08	2.47	547	1575.6
12	5.25	3.22	2.03	381	1250.8
13	4.44	2.69	1.75	204	739.4
14	4.90	2.96	1.94	234	791.8
15	6.36	4.04	2.32	235	705.8
16	6.06	3.65	2.41	227	664.7
17	3.14	1.84	1.30	213	941.2
18	6.15	3.97	2.18	555	1737.4
19	3.81	2.27	1.54	214	844.6
20	4.29	2.67	1.62	488	1862.0
21	5.32	3.14	2.18	200	626.1
22	4.91	3.19	1.72	283	1037.6
23	4.80	2.84	1.96	481	1616.4
24	6.77	4.05	2.72	410	1107.4
25	8.21	4.90	3.31	520	1232.2
26	8.80	5.25	3.55	500	1130.8
27	5.89	3.74	2.15	511	1614.5
28	6.87	4.16	2.71	410	1110.2
29	6.16	3.73	2.43	135	393.1
30	4.97	3.04	1.93	504	1711.2
31	5.52	3.22	2.30	263	794.4
32	3.86	2.27	1.59	394	1522.2
33	3.30	1.85	1.45	276	1133.9
34	3.79	2.27	1.52	514	2046.4
35	4.27	2.61	1.66	414	1554.2
36	4.00	2.38	1.62	643	2453.5
37	3.88	2.28	1.60	345	1327.4
38	3.92	2.38	1.54	428	1689.2
39	4.30	2.52	1.78	262	938.9
40	3.87	2.36	1.51	550	2199.3
41	5.07	3.03	2.04	235	768.9
42	9.14	6.06	3.08	1028	2555.9
43	7.28	4.39	2.89	288	747.1
44	7.03	4.03	3.00	206	521.2
45	4.43	2.52	1.91	435	1487.2
46	5.11	2.98	2.13	502	1596.0
47	6.78	3.93	2.85	297	777.6
48	5.80	3.41	2.39	285	839.1
49	5.40	3.17	2.23	557	1717.5
50	4.01	2.31	1.70	234	864.6
51	2.28	1.36	0.92	359	1997.5
52	6.76	4.07	2.69	552	1502.0
Average	5.75	3.50	2.26	415	1300.6

APPENDIX IV

Weight percentages of products in each run of the ERC abrasion mixer experiment and their grain size compositions

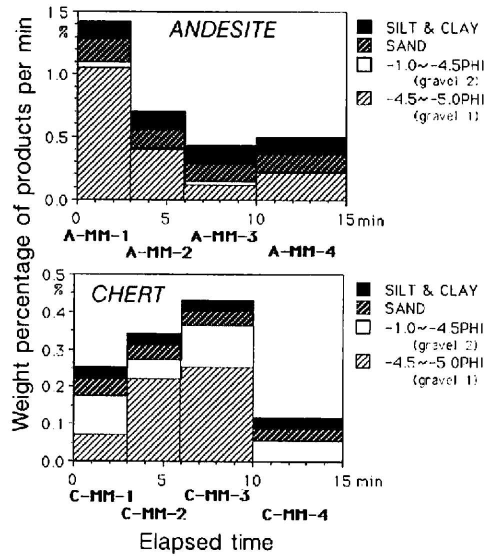

Fig.A4.1 Weight percentages of products in each run of M-size uniform cases and their grain size compositions. Width of each bar is proportional to experimental run time. (regarding gravel 1 or 2, see text for explanation)

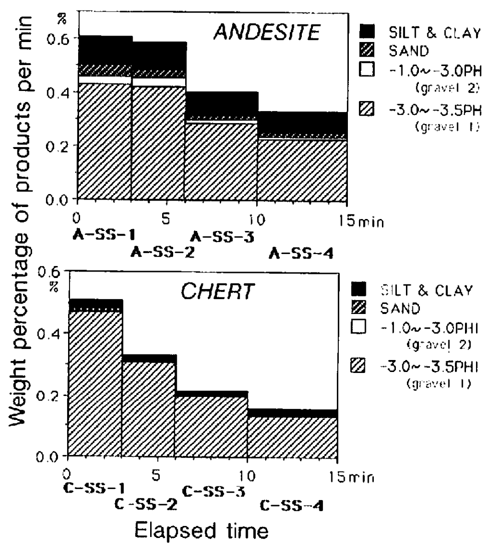

Fig.A4.2 Weight percentages of products in each run of S-size uniform cases and their grain size compositions. Width of each bar is proportional to experimental run time. (regarding gravel 1 or 2, see text for explanation)

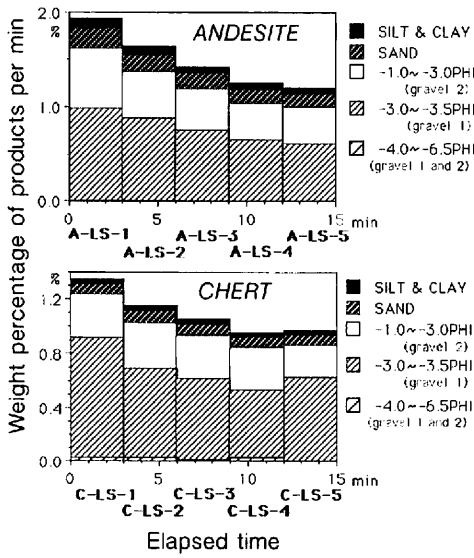

Fig.A4.3 Weight percentages of products in each run of LS-size mixed cases and their grain size compositions. Width of each bar is proportional to experimental run time.
(regarding gravel 1 or 2, see text for explanation)

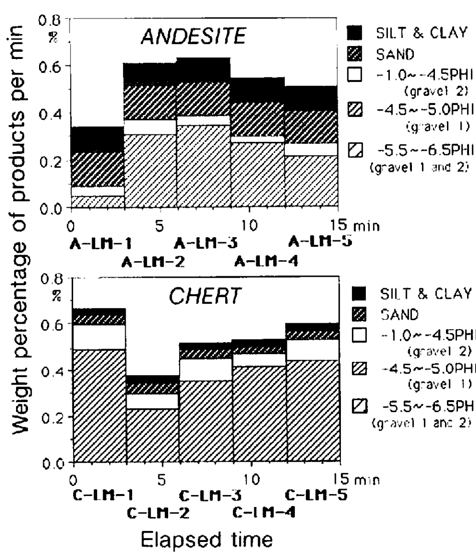

Fig.A4.4 Weight percentages of products in each run of LM-size mixed cases and their grain size compositions. Width of each bar is proportional to experimental run time.
(regarding gravel 1 or 2, see text for explanation)

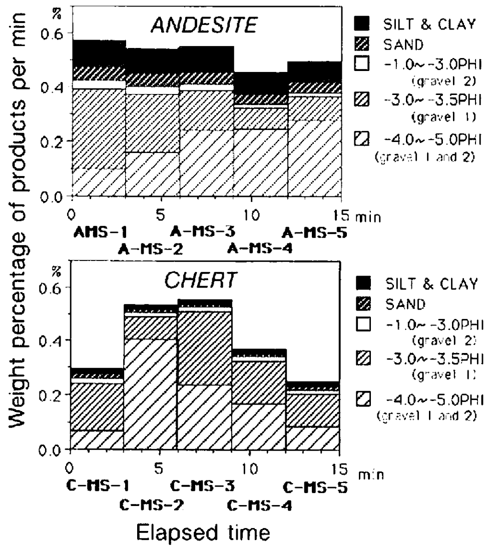

Fig.A4.5 Weight percentages of products in each run of MS-size mixed cases and their grain size compositions. Width of each bar is proportional to experimental run time.
(regarding gravel 1 or 2, see text for explanation)

APPENDIX V

Roundness of andesite and chert gravel particles sampled from the bed material of the Watarase River

Table A5 Roundness of andesite and chert gravels in each size class sampled from the bed material of the Watarase River, site No.6.

Grain size		andesite	chert
ϕ		Roundness	
−7.0<	<−6.5	0.84	0.75
−6.5<	<−6.0	0.74	0.53
−6.0<	<−5.5	0.84	0.61
−5.5<	<−5.0	0.80	0.59
−5.0<	<−4.5	0.71	0.54
−4.5<	<−4.0	0.72	0.57
−4.0<	<−3.5	0.69	0.49
−3.5<	<−3.0	0.58	0.43
−3.0<	<−2.5	0.51	0.42
−2.5<	<−2.0	0.47	0.38
−2.0<	<−1.5	0.44	0.38
−1.5<	<−1.0	0.37	0.41

Roundness is the average of 30 particles in each size class.

APPENDIX VI

Diminution coefficients obtained from the ERC abrasion mixer experiment

Table A6.1 Summary of diminution coefficients obtained from the ERC abrasion mixer experiment.

Experimental case:	Size	Size diminution coefficient (km^{-1}) a_d	a_{dG1}	Experimental case:	Size	Size diminution coefficient (km^{-1}) a_d	a_{dG1}
A-LL:	L	0.01419	0.01419	C-LL:	L	0.05029	0.02461
A-MM:	M	0.04057	0.01784	C-MM:	M	0.01555	0.00833
A-SS:	S	0.02615	0.00765	C-SS:	S	0.01590	0.00149
A-LM:	L	0.01330	0.01330	C-LM:	L	0.00349	0.00318
A-LM:	M	0.04766	0.02056	C-LM:	M	0.06029	0.01427
A-LS:	L	0.00548	0.00548	C-LS:	L	0.00539	0.00539
A-LS:	S	0.19049	0.08533	C-LS:	S	0.13095	0.04709
A-MS:	M	0.03288	0.00950	C-MS:	M	0.02358	0.00356
A-MS:	S	0.02673	0.00812	C-MS:	S	0.02201	0.00377

Regarding a_d and a_{dG1}, see text or **tables A6.2 and A6.3** for explanation.

Table A6.2 Procedures of calculating diminution coefficients of andesite from the ERC abrasion mixer experiment.

Experimental case-run:	Gravel size	Run time (min) ①	Initial weight (g) W_0 ②	Weight after each run (g) Test size W ③	Gravel 1 ④	Sum W_{G1} ⑤	Equivalent distance (km) X ⑥	Size diminution coefficient (km^{-1}) a_d ⑦	a_{dG1} ⑧
A-LL-1:	L	3	30864	30751	0.00	30751.00	0.17671	0.00692	0.00692
A-LL-2:	L	4	30751	30532	0.00	30532.00	0.23562	0.01011	0.01011
A-LL-3:	L	3	30532	30319	0.00	30319.00	0.17671	0.01321	0.01321
A-LL-4:	L	5	30319	29725	0.00	29725.00	0.29452	0.02239	0.02239
							average ⇨	0.01419	0.01419
A-MM-1:	M	3	30157	28874	951.60	29825.60	0.17671	0.08201	0.02084
A-MM-2:	M	3	28874	28267	347.50	28614.50	0.17671	0.04008	0.01703
A-MM-3:	M	4	28267	27777	127.50	27904.50	0.23562	0.02474	0.01826
A-MM-4:	M	5	27777	27082	300.20	27382.20	0.29452	0.02868	0.01620
							average ⇨	0.04057	0.01784
A-SS-1:	S	3	30000	29452	388.88	29840.88	0.17671	0.03477	0.01003
A-SS-2:	S	3	29452	28932	373.08	29305.08	0.17671	0.03360	0.00943
A-SS-3:	S	4	28932	28464	333.10	28797.10	0.23562	0.02307	0.00661
A-SS-4:	S	5	28464	27991	323.19	28314.19	0.29452	0.01897	0.00597
							average ⇨	0.02615	0.00765
A-LM-1:	L	3	15276	15167	0.00	15167.00	0.17671	0.01351	0.01351
A-LM-2:	L	3	15167	15096	0.00	15096.00	0.17671	0.00885	0.00885
A-LM-3:	L	3	15096	14895	0.00	14895.00	0.17671	0.02528	0.02528
A-LM-4:	L	3	14895	14871	0.00	14871.00	0.17671	0.00304	0.00304
A-LM-5:	L	3	14871	14747	0.00	14747.00	0.17671	0.01579	0.01579
							average ⇨	0.01330	0.01330
A-LM-1:	M	3	15276	15076	43.38	15119.38	0.17671	0.02486	0.01944
A-LM-2:	M	3	15076	14590	257.79	14847.79	0.17671	0.06181	0.02877
A-LM-3:	M	3	14590	14227	303.36	14530.36	0.17671	0.04752	0.00773
A-LM-4:	M	3	14227	13776	233.91	14009.91	0.17671	0.06076	0.02900
A-LM-5:	M	3	13776	13463	183.18	13646.18	0.17671	0.04335	0.01786
							average ⇨	0.04766	0.02056
A-LS-1:	L	3	14965	14935	0.00	14935.00	0.17671	0.00379	0.00379
A-LS-2:	L	3	14935	14895	0.00	14895.00	0.17671	0.00506	0.00506
A-LS-3:	L	3	14895	14850	0.00	14850.00	0.17671	0.00571	0.00571
A-LS-4:	L	3	14850	14800	0.00	14800.00	0.17671	0.00636	0.00636
A-LS-5:	L	3	14800	14749	0.00	14749.00	0.17671	0.00651	0.00651
							average ⇨	0.00548	0.00548
A-LS-1:	S	3	14965	13252	883.00	14135.00	0.17671	0.22931	0.10763
A-LS-2:	S	3	13252	11902	746.50	12648.50	0.17671	0.20267	0.08792
A-LS-3:	S	3	11902	10796	604.76	11400.76	0.17671	0.18397	0.08116
A-LS-4:	S	3	10796	9874	504.05	10378.05	0.17671	0.16839	0.07448
A-LS-5:	S	3	9874	9032	454.81	9486.81	0.17671	0.16813	0.07546
							average ⇨	0.19049	0.08533
A-MS-1:	M	3	15013	14786	91.43	14877.43	0.17671	0.02874	0.01711
A-MS-2:	M	3	14786	14586	141.66	14727.66	0.17671	0.02569	0.00746
A-MS-3:	M	3	14586	14314	209.65	14523.65	0.17671	0.03551	0.00808
A-MS-4:	M	3	14314	14055	209.78	14264.78	0.17671	0.03444	0.00650
A-MS-5:	M	3	14055	13760	232.91	13992.91	0.17671	0.04001	0.00835
							average ⇨	0.03288	0.00950
A-MS-1:	S	3	15013	14723	259.29	14982.29	0.17671	0.03679	0.00386
A-MS-2:	S	3	14723	14443	187.61	14630.61	0.17671	0.03622	0.01187
A-MS-3:	S	3	14443	14238	128.67	14366.67	0.17671	0.02697	0.01000
A-MS-4:	S	3	14238	14109	66.12	14175.12	0.17671	0.01717	0.00835
A-MS-5:	S	3	14109	13986	74.49	14060.49	0.17671	0.01652	0.00650
							average ⇨	0.02673	0.00812

①, ②, ③ and ④ are data from **tables 3.2 and 3.3**

⑤ = ③ + ④, ⑥ = ① × 0.00075 × π × 25, ⑦ = −1/⑥ × ln (③/②)/3, ⑧ = −1/⑥ × ln (⑤/②)/3

Table A6.3 Procedures of calculating diminution coefficients of chert from the ERC abrasion mixer experiment.

Experimental case-run:	Gravel size	Run time (min) ①	Initial weight (g) W_0 ②	Weight after each run (g) Test size W ③	Gravel 1 ④	Sum W_{G1} ⑤	Equivalent distance (km) X ⑥	Size diminution coefficient (km^{-1}) a_d ⑦	a_{dG1} ⑧
C-LL-1:	L	3	29664	28134	774.00	28908.00	0.17671	0.09989	0.04870
C-LL-2:	L	3	28134	28000	0.00	28000.00	0.17671	0.00901	0.00901
C-LL-3:	L	4	28000	27592	0.00	27592.00	0.23562	0.02077	0.02077
C-LL-4:	L	5	27592	25962	1084.60	27046.60	0.29452	0.06892	0.02260
							average ⇨	0.05029	0.02461
C-MM-1:	M	3	30047	29820	64.31	29884.31	0.17671	0.01430	0.01024
C-MM-2:	M	3	29820	29514	198.54	29712.54	0.17671	0.01946	0.00681
C-MM-3:	M	4	29514	29003	299.30	29302.30	0.23562	0.02471	0.01018
C-MM-4:	M	5	29003	28834	0.00	28834.00	0.29452	0.00661	0.00661
							average ⇨	0.01555	0.00833
C-SS-1:	S	3	30003	29542	424.20	29966.20	0.17671	0.02921	0.00232
C-SS-2:	S	3	29542	29247	272.20	29519.20	0.17671	0.01893	0.00146
C-SS-3:	S	4	29247	28990	233.81	29223.81	0.23562	0.01249	0.00112
C-SS-4:	S	5	28990	28765	191.14	28956.14	0.29452	0.00882	0.00132
							average ⇨	0.01590	0.00149
C-LM-1:	L	3	15261	15237	0.00	15237.00	0.17671	0.00297	0.00297
C-LM-2:	L	3	15237	15215	0.00	15215.00	0.17671	0.00273	0.00273
C-LM-3:	L	3	15215	15189	0.00	15189.00	0.17671	0.00323	0.00323
C-LM-4:	L	3	15189	15161	0.00	15161.00	0.17671	0.00348	0.00348
C-LM-5:	L	3	15161	15133	0.00	15133.00	0.17671	0.00349	0.00349
							average ⇨	0.00318	0.00318
C-LM-1:	M	3	15261	14676	451.27	15127.27	0.17671	0.07373	0.01660
C-LM-2:	M	3	14676	14363	205.87	14568.87	0.17671	0.04066	0.01382
C-LM-3:	M	3	14363	13927	310.67	14237.67	0.17671	0.05815	0.01653
C-LM-4:	M	3	13927	13493	365.25	13858.25	0.17671	0.05972	0.00933
C-LM-5:	M	3	13493	13007	378.77	13385.77	0.17671	0.06920	0.01505
							average ⇨	0.06029	0.01427
C-LS-1:	L	3	15303	15263	0.00	15263.00	0.17671	0.00494	0.00494
C-LS-2:	L	3	15263	15213	0.00	15213.00	0.17671	0.00619	0.00619
C-LS-3:	L	3	15213	15192	0.00	15192.00	0.17671	0.00261	0.00261
C-LS-4:	L	3	15192	15122	0.00	15122.00	0.17671	0.00871	0.00871
C-LS-5:	L	3	15122	15086	0.00	15086.00	0.17671	0.00450	0.00450
							average ⇨	0.00539	0.00539
C-LS-1:	S	3	15303	14107	820.20	14927.20	0.17671	0.15350	0.04690
C-LS-2:	S	3	14107	13142	586.30	13728.30	0.17671	0.13366	0.05133
C-LS-3:	S	3	13142	12269	520.10	12789.10	0.17671	0.12966	0.05134
C-LS-4:	S	3	12269	11554	417.40	11971.40	0.17671	0.11326	0.04632
C-LS-5:	S	3	11554	10815	499.20	11314.20	0.17671	0.12468	0.03956
							average ⇨	0.13095	0.04709
C-MS-1:	M	3	15000	14920	0.00	14920.00	0.17671	0.01009	0.01009
C-MS-2:	M	3	14920	14548	358.90	14906.90	0.17671	0.04763	0.00166
C-MS-3:	M	3	14548	14324	206.33	14530.33	0.17671	0.02927	0.00229
C-MS-4:	M	3	14324	14167	146.56	14313.56	0.17671	0.02079	0.00138
C-MS-5:	M	3	14167	14091	57.97	14148.97	0.17671	0.01015	0.00240
							average ⇨	0.02358	0.00356
C-MS-1:	S	3	15000	14813	151.70	14964.70	0.17671	0.02366	0.00444
C-MS-2:	S	3	14813	14708	77.94	14785.94	0.17671	0.01342	0.00345
C-MS-3:	S	3	14708	14445	242.12	14687.12	0.17671	0.03403	0.00268
C-MS-4:	S	3	14445	14286	130.54	14416.54	0.17671	0.02088	0.00372
C-MS-5:	S	3	14286	14150	101.56	14251.56	0.17671	0.01804	0.00455
							average ⇨	0.02201	0.00377

①, ②, ③ and ④ are data from **tables 3.2 and 3.3**

⑤ = ③ + ④, ⑥ = ① × 0.00075 × π × 25, ⑦ = −1/⑥ × ln (③/②)/3, ⑧ = −1/⑥ × ln (⑤/②)/3

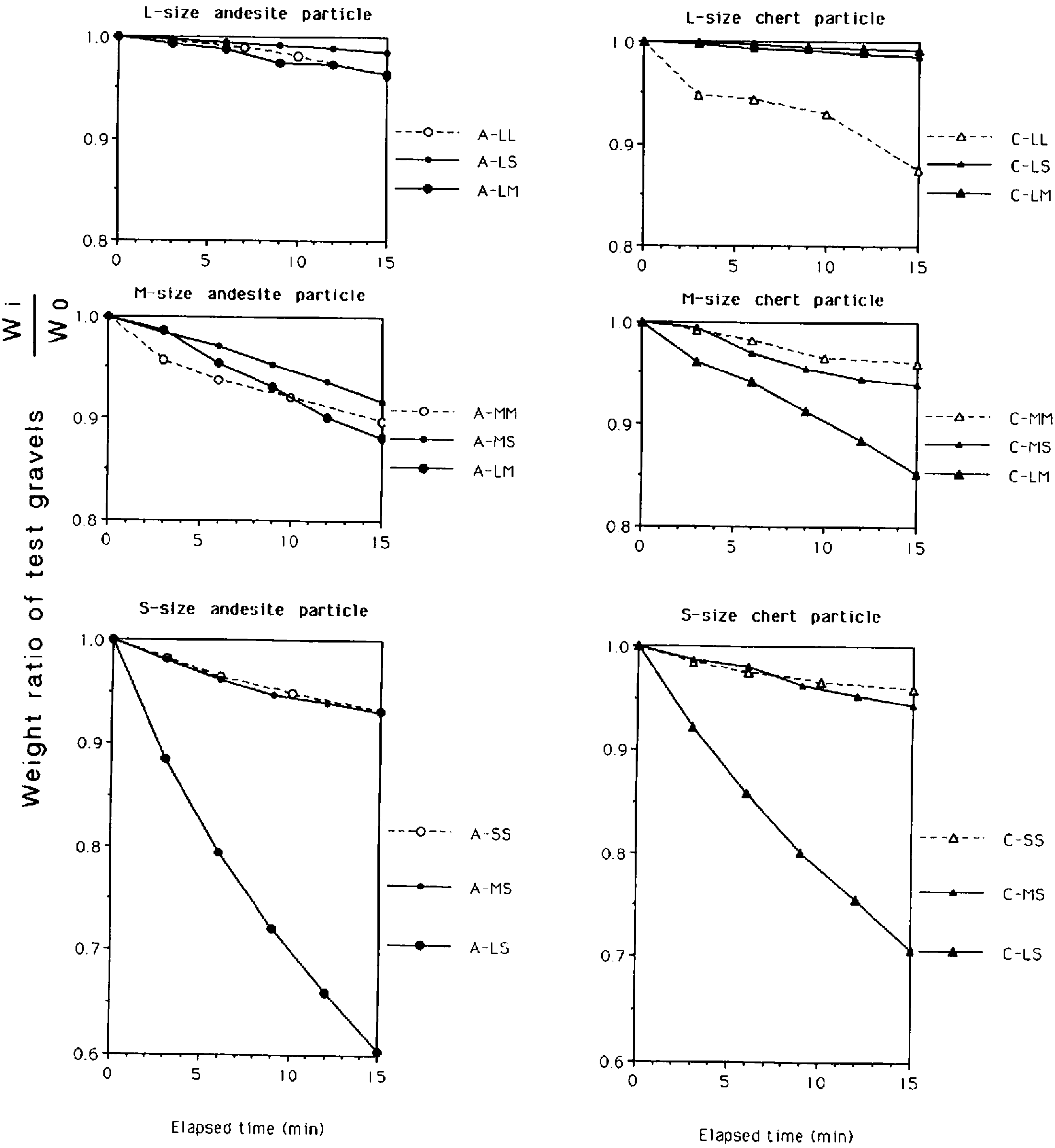

Fig.A6.1 Decrease in weight of test gravel particles. Open circles and triangles with a dashed line show uniform size experiment, while closed with a solid line show mixed size experiment. W_0 is an initial weight of test gravels of the first run, and W_i is a weight of test gravels of each run.

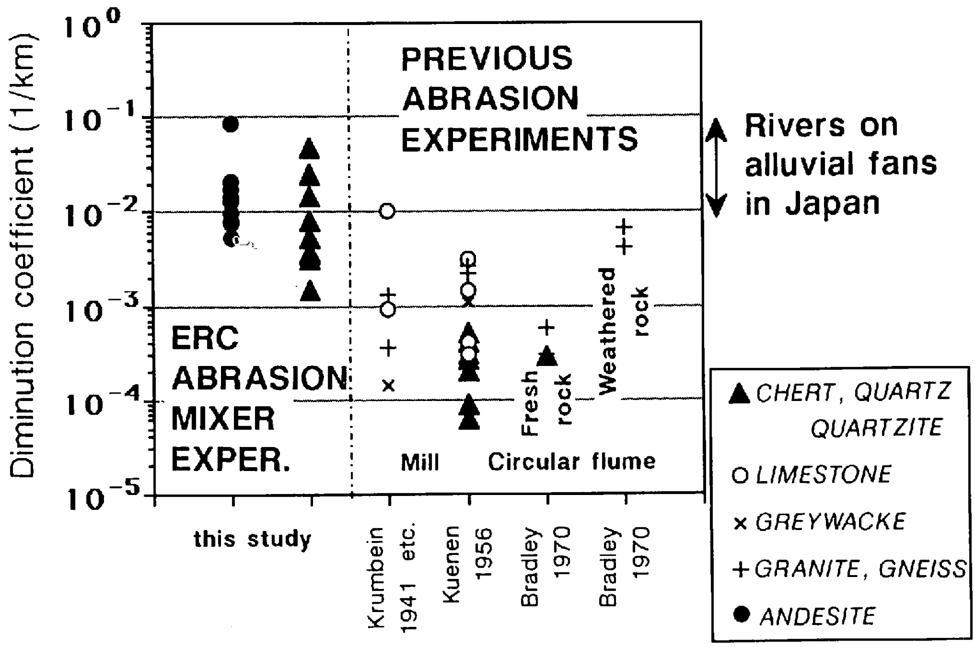

Fig.A6.2 Comparison of diminution coefficients obtained from the ERC abrasion mixer experiment with those from previous experimental studies. Diminution coefficients of previous experimental studies and of many Japanese rivers on alluvial fans are after Shaw and Kellerhals (1982, table 12). Diminution coefficients of the ERC abrasion mixer experiment are a_{dG1} (column ⑧) in **tables A6.1 ～ A6.3**.

APPENDIX VII

Photos of test gravel particles before and after the ERC abrasion mixer experiment

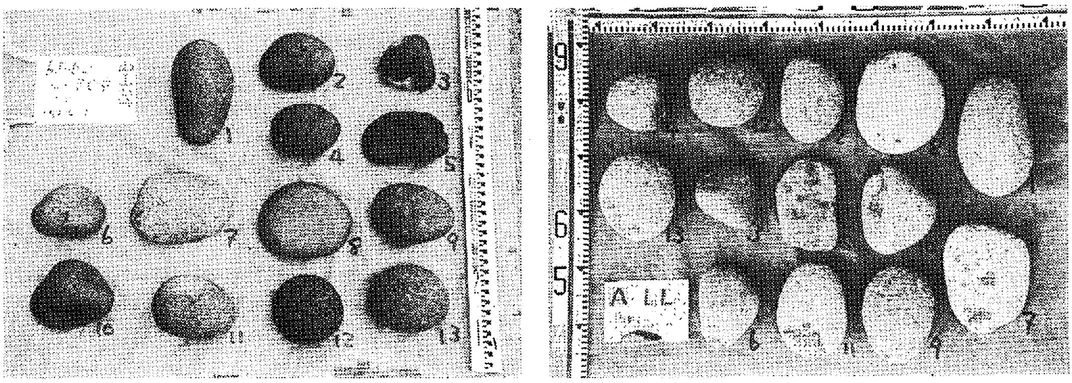

Fig.A7.1 All of andesite test gravels used in the L-size uniform case.
Left photo: Before experiment.
Right: After A-LL-4.

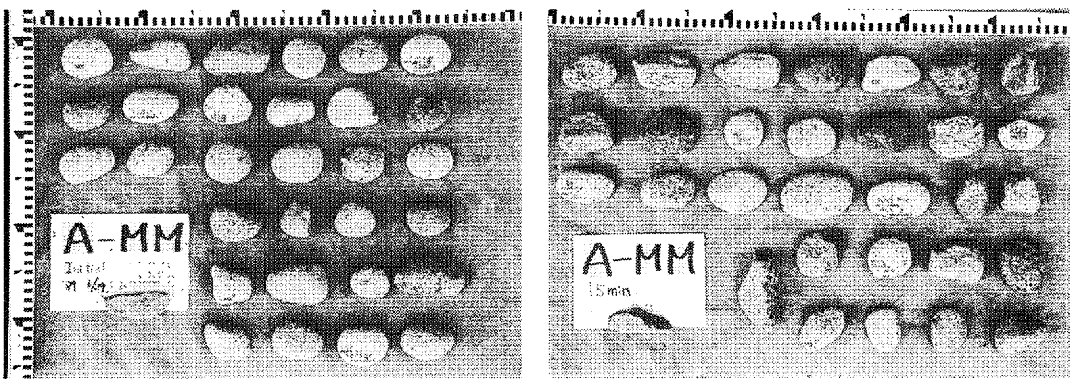

Fig.A7.2 Sample of andesite test gravels used in the M-size uniform case.
Left photo: Before experiment.
Right: After A-MM-4.

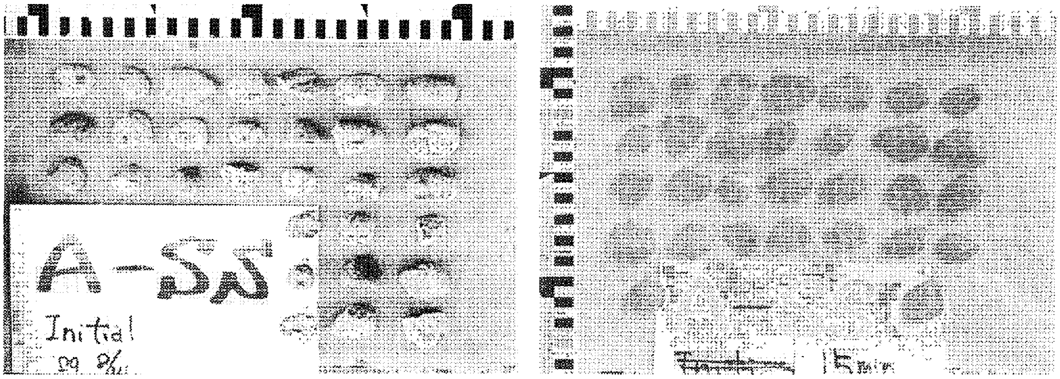

Fig.A7.3 Sample of andesite test gravels used in the S-size uniform case.
Left photo: Before experiment.
Right: After A-SS-4.

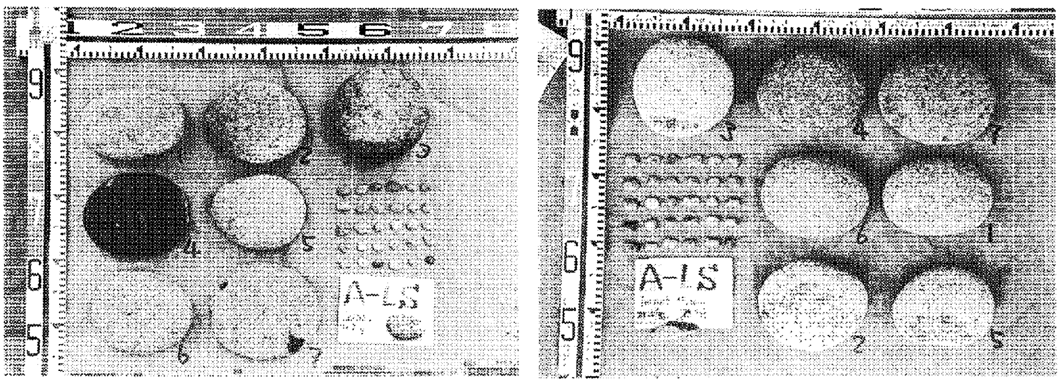

Fig.A7.4 Andesite test gravels used in the LS mixed case.
All of L-size gravels and sample of S-size gravels.
Left photo: Before experiment.
Right: After A-LS-5.

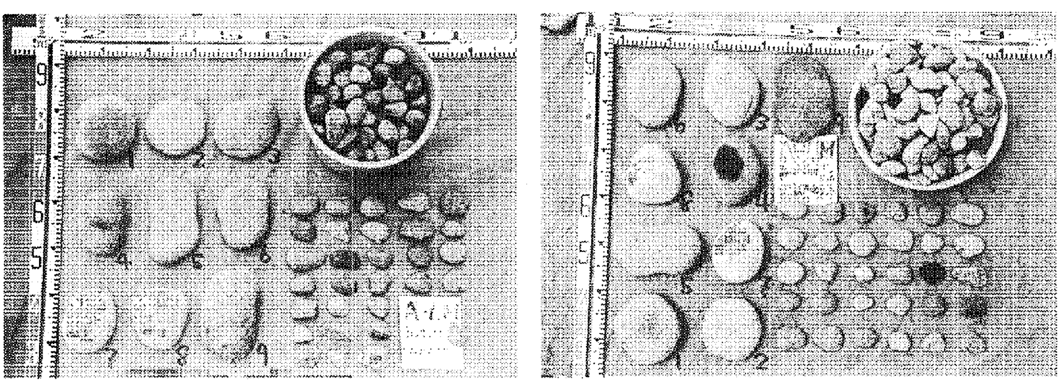

Fig.A7.5 Andesite test gravels used in the LM mixed case.
All of L-size gravels and sample of M-size gravels.
Left photo: Before experiment.
Right: After A-LM-5.

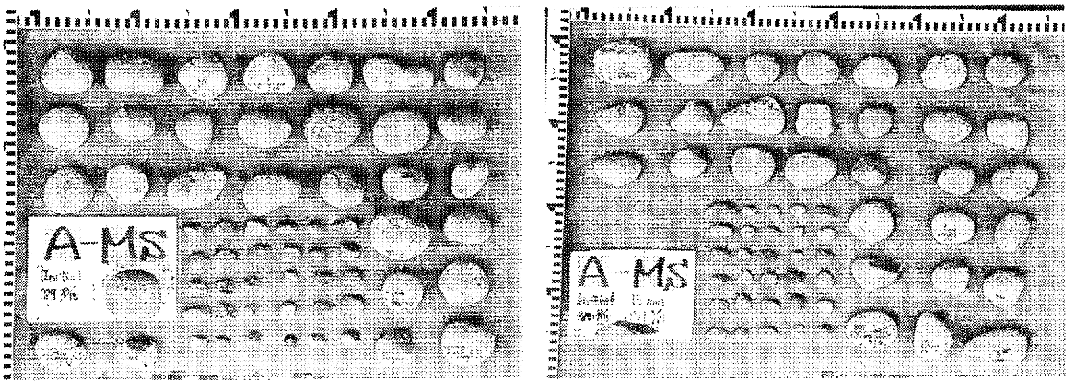

Fig.A7.6 Sample of andesite test gravels used in the MS mixed case.
Left photo: Before experiment.
Right: After A-MS-5.

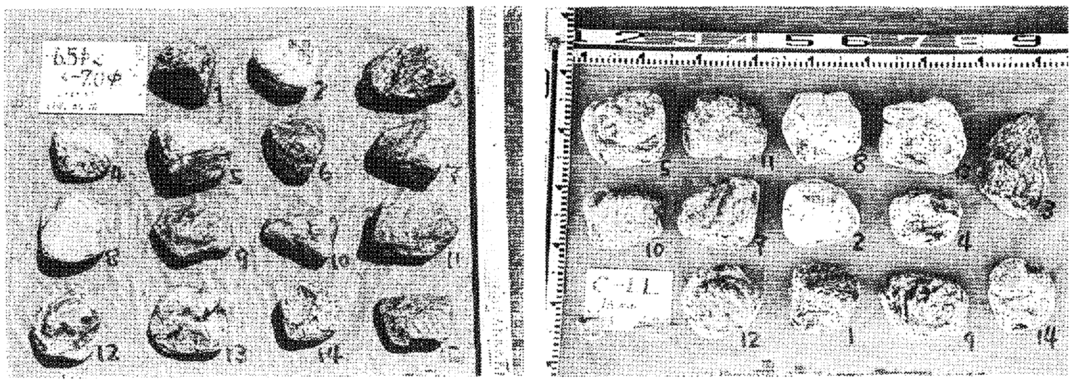

Fig.A7.7 All of chert test gravels used in the L-size uniform case.
Left photo: Before experiment.
Right: After C-LL-4.

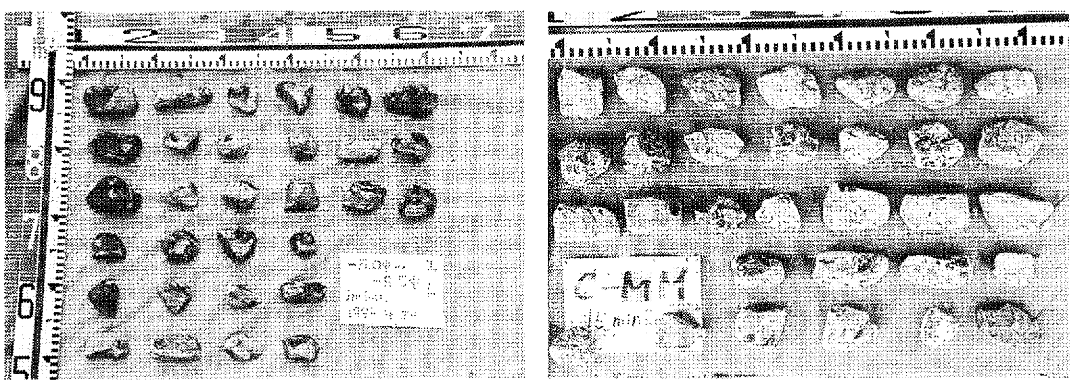

Fig.A7.8 Sample of chert test gravels used in the M-size uniform case.
Left photo: Before experiment.
Right: After C-MM-4.

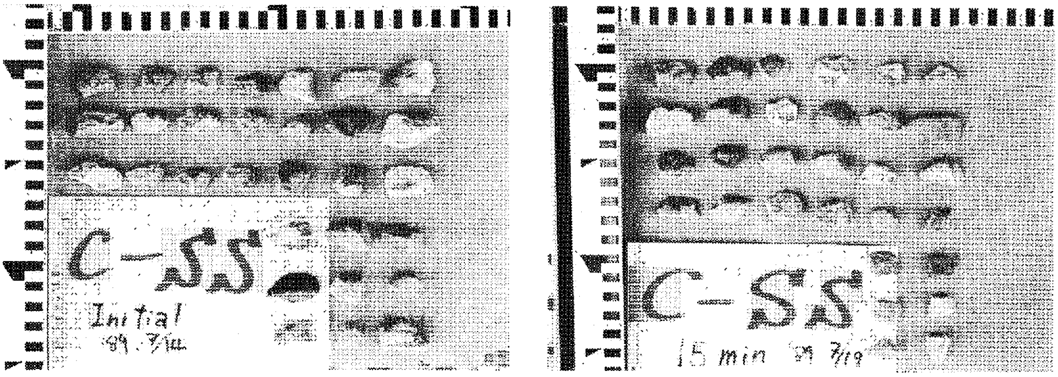

Fig.A7.9 Sample of chert test gravels used in the S-size uniform case.
Left photo: Before experiment.
Right: After C-SS-4.

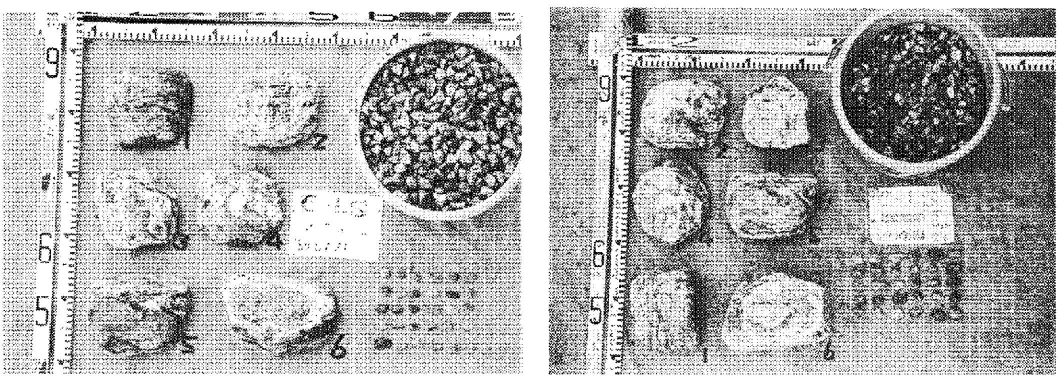

Fig.A7.10 Chert test gravels used in the LS mixed case.
All of L-size gravels and sample of S-size gravels.
Left photo: Before experiment.
Right: After C-LS-5.

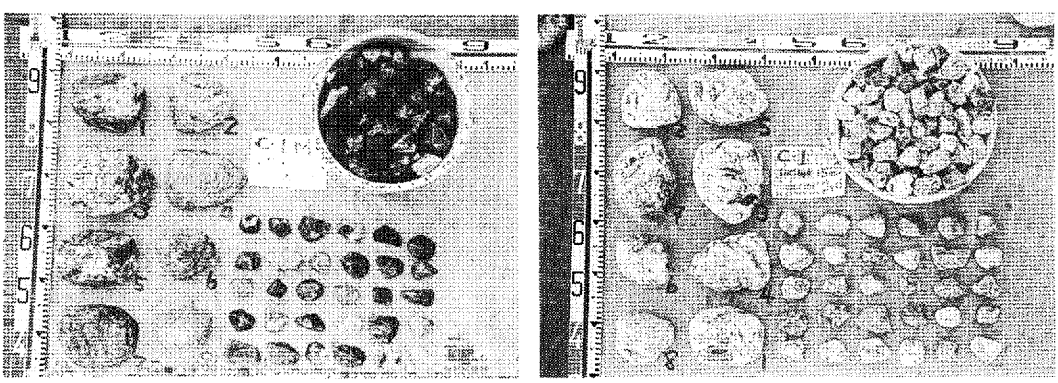

Fig.A7.11 Chert test gravels used in the LM mixed case.
All of L-size gravels and sample of M-size gravels.
Left photo: Before experiment.
Right: After C-LM-5.

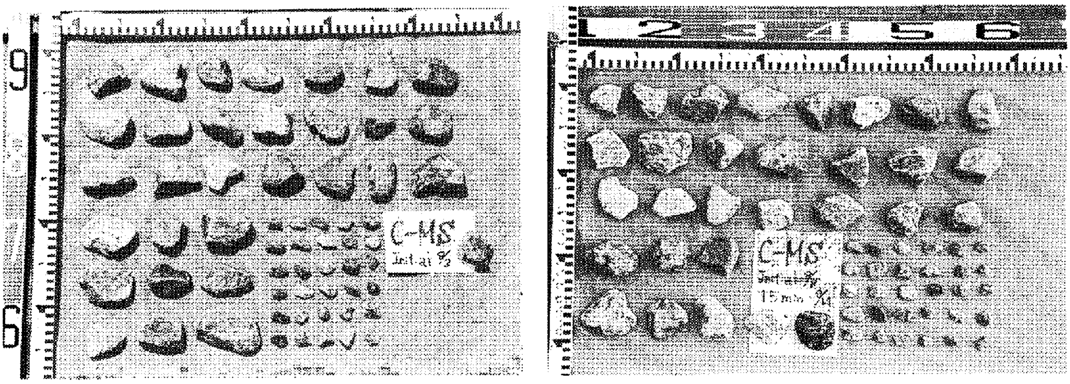

Fig.A7.12 Sample of chert test gravels used in the MS mixed case.
Left photo: Before experiment.
Right: After C-MS-5.

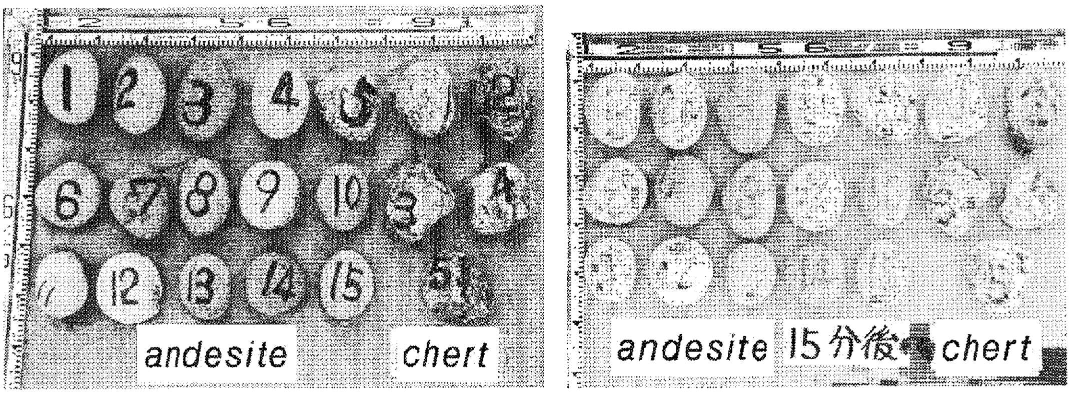

Fig.A7.13 All test gravels used in the lithologic mixture case (A15C05).
Left photo: Before experiment.
Right: After A15C05-3.

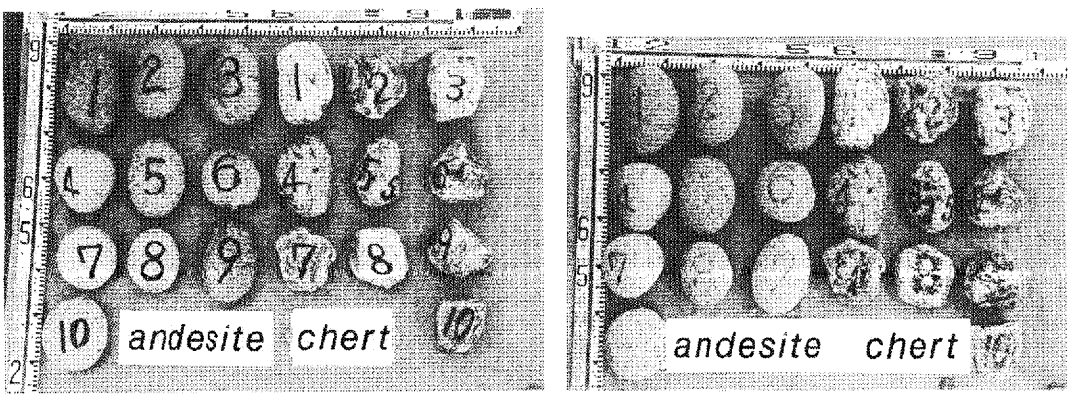

Fig.A7.14 All test gravels used in the lithologic mixture case (A10C10).
Left photo: Before experiment.
Right: After A10C10-3.

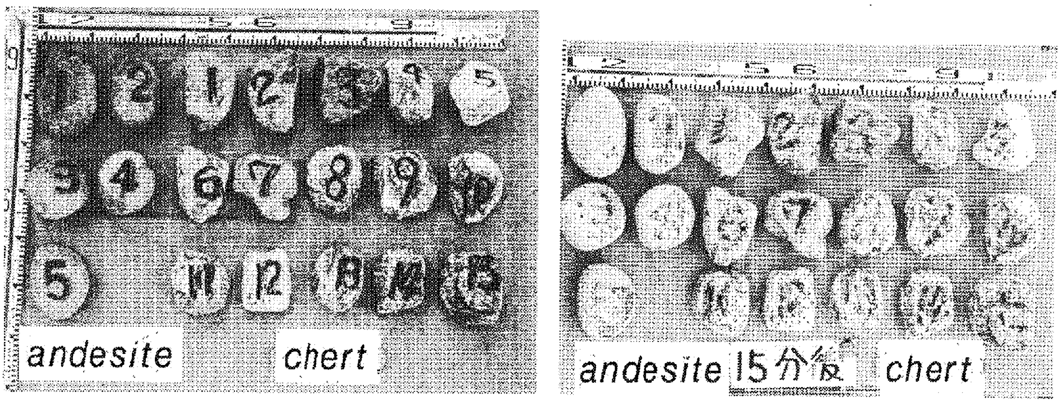

Fig.A7.15 All test gravels used in the lithologic mixture case (A05C15).
Left photo: Before experiment.
Right: After A05C15-3.

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