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DEVELOPMENT OF A NEW GEOMATERIAL FOR BASE ISOLATION FOUNDATIONS

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ABSTRACT

Design method of rational composite foundation capable of reducing seismic response of structures was studied. Analysis of the effects of damping materials on the reduction of seismic response of a full-scale structure was performed. Shaking experiment and seismic observation for model foundations confirming the damping effects were conducted and development of new damping material are described.

INTRODUCTION

Validity of a new design method, seismic absorbing or isolation structures, was confirmed through earthquakes at Hyogoken-nanbu in 1995 and Niigata-chuetsu offshore in 2004. However, many mid/high rise buildings at urban area in Japan are built on soft grounds that are not good enough in terms of structural design. Hence structures equipped with conventional seismic-absorbing or isolation system may suffer from doubled cost burden, pile driving and base-isolation device, which lead to interruption of its wide dissemination.

Development of a rational seismic design and a composite foundation for soft grounds capable of depressing seismic response were aimed in this study through shaking experiments of foundation blocks built on an improved ground.

Table 1 Properties of other materials of upper-structure

Node	Element	Height (m)	Mass (ton)	Shearing section area	Moment of inertia (m^4)
6		22.5	890		
	⑤			0.3394	1280
5		19	890		
	④			0.3394	1280
4		15.5	890		
	③			0.3394	1280
3		12	890		
	②			0.384	1280
2		8.5	890		
	①			0.384	1280
Foundation		-	2920		

This paper comprises following three parts:

(1) Analytical study of seismic response depression of a full-scale structure,

(2) Shaking experiment and seismic observation for the damping effects,

(3) Development of a damping material comprising industrial wastes and asphalt.

Installation of buffer materials around the foundation of the building can prevent vibration propagation mainly for traffic

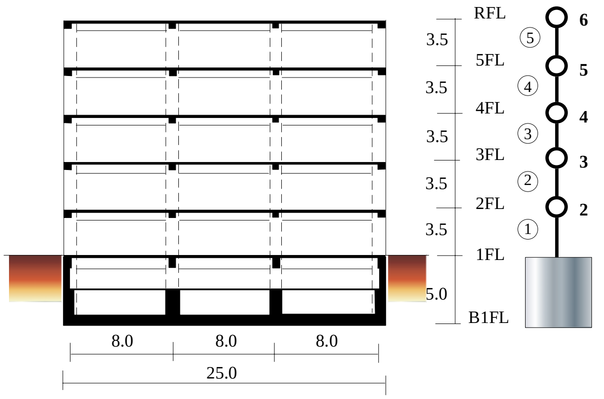


Fig.1 Analysis model of superstructure

Table 2 Analysis cases (soil and foundation)

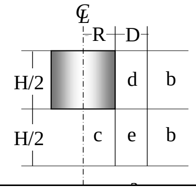
Case	a	b	c	d	e	
A	I	II	II	II	II	
B	I	II	III	II	II	
C	I	II	III	IV	II	
D	I	II	III	IV	IV	

Table 3 Properties of soil and other materials

		Vs (m/s)	L (ton/m^3)	n	h
I	Supported soil	200	1.8	0.45	0.02
II	Surface layered	100	1.6	0.45	0.02
III	Improved soil	130	1.7	0.45	0.02
IV	Damping mixture	165	1.7	0.35	0.2

and construction vibrations. Few studies are known for the seismic vibration reduction except for that of Hirota *et al*. (1993) and Ishimaru *at al*. (2004).

ANALYSIS OF SEISMIC RESPONSE DAMPING OF A FULL-SCALE STRUCTURE

Outline

Seismic response analysis was performed for an office building with a framed structure of 25m-square plan, 5-story and a basement to evaluate the effects of damping device, when installed around foundation, on the seismic response of the structure.

Building and Ground Models

Model building was an office building with a framed structure of 25m-square plan, 5-story and a basement as shown in Fig. 1. The upper ground story height was 3.5m and that of sub ground was 5m including foundation. The framed structure was modeled as a frame model and the eigenvalue analysis was performed with the foundation top as a fixed point. The frame model was analyzed under incremental loading. Shear cross-sections and moment of second order of each story were calculated from the load-displacement relations and a mass system model was built assuming each story mass can be concentrated to each floor mass. Eigenvalue analysis of the mass system was performed and member performance was controlled to coincide with the first order frequency of the eigenvalue analysis of the frame model. Basement floor was assumed to be a rigid body on which total mass of the upper floors was uniformly imposed. Parameters of the superstructure are shown in Table 1.

Ground and foundation were analyzed with the axisymmetric model. Equivalent radius of the foundation was R=14.105m and the ground was regarded as a 2-layer ground with a surface layer of 10m thick. Velocities of shear wave of the surface layer and the bearing ground were *V*s=100m/s and *V*s=200m/s respectively.

Cases of Analysis

Use of the original ground without any improvement is the analysis Case A, and Case B, C and D with ground improvements or damping device are compared with respect to Case A as shown in Table 2. In Case B, ground improvement is made directly under the foundation. In Case C, a seismic damping material of asphalt-rubber chip composite was

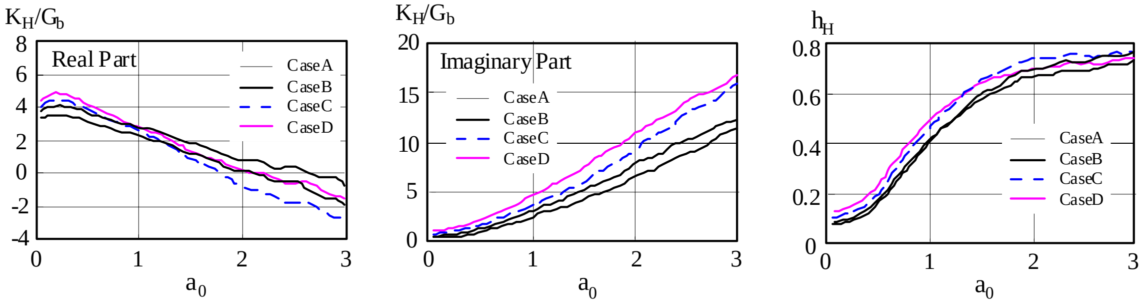


Fig. 2 Sway impedance functions

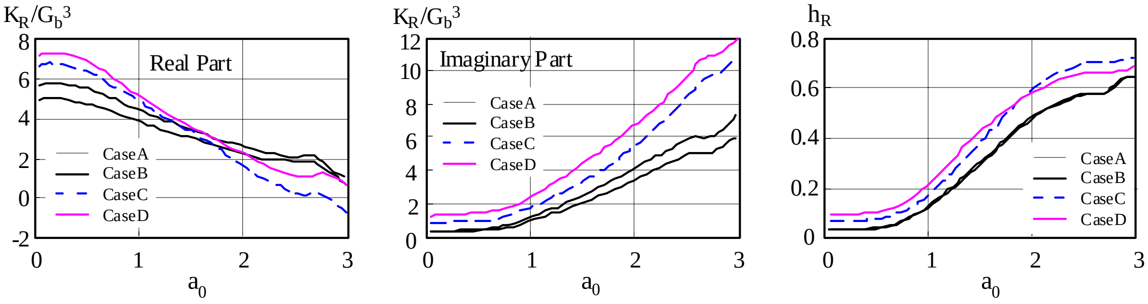


Fig. 3 Rocking impedance functions

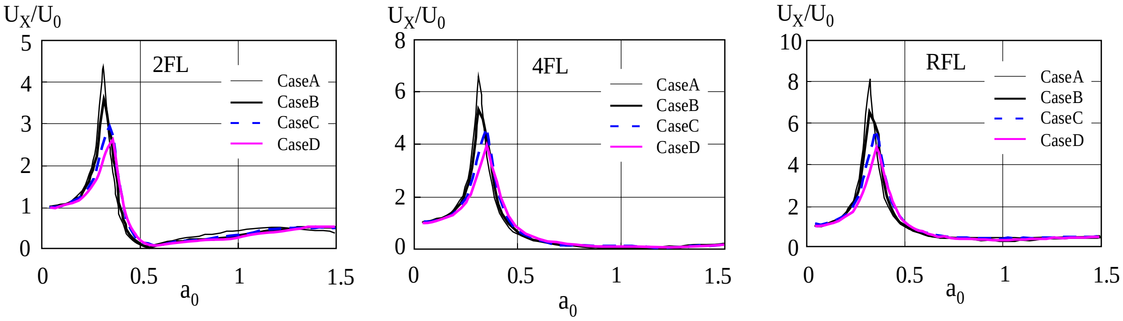


Fig.4 Transfer functions against free field soil

installed around the foundation with a depth of 4m. In Case D, the depth of the damping layer was extended over the bearing ground. Properties of each component were determined on the basis of material tests as shown in Table 3. Elastic modulus and damping constant of the damping material comprising asphalt, gravel and rubber-chip were determined through a dynamic tri-axial compression test with a specimen of 100mm in diameter and 190mm in height. An equivalent elastic modulus was 120MPa and an equivalent damping constant was approx. 20% at a low strain region of variable loading at a restraint pressure of 50kPa and a loading frequency of 0.1Hz.

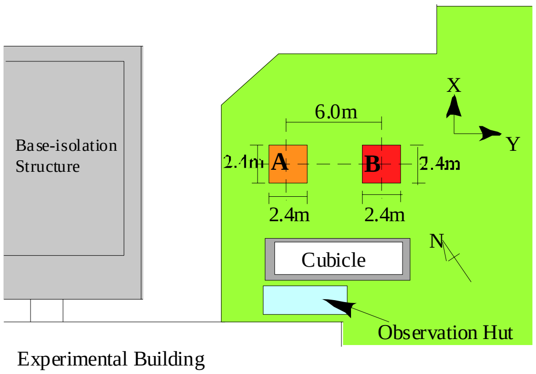


Fig. 5 Schematic view of the experimental site

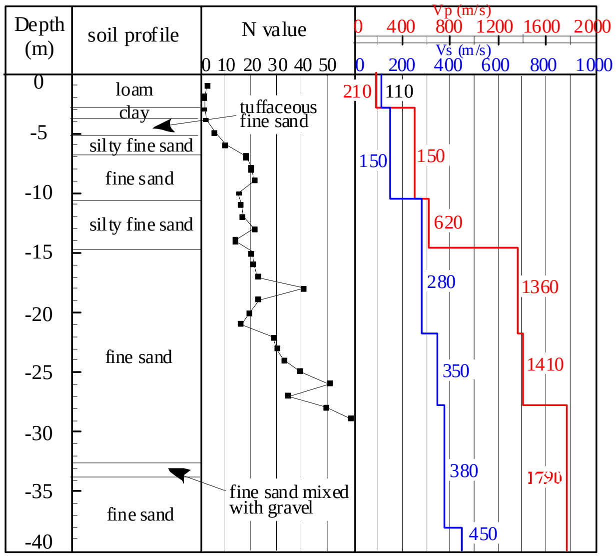


Fig. 6 Soil profile of the experiment site

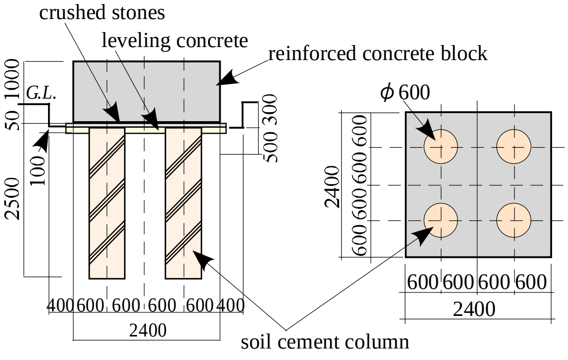


Fig. 7 Foundation block

Result and Discussion

Ground impedance and equivalent damping constant. Swaying, rocking and coupled swaying-rocking components were compared by analysis case. The real and imaginary parts of the swaying K_H and rocking K_R impedance and the equivalent damping factors h_H, h_R are shown in Figs 2 and 3. In both figures, non-dimensional frequency $a_0=\omega b/Vs$ is shown in horizontal axis where ω is circular frequency, b is the half width of the rectangle foundation and Vs is the shear wave velocity of the bearing ground (200m/s), while for vertical axis, a non-dimensional stiffness normalized with shear modulus of the bearing ground and half width of the rectangular foundation. Effects of shear wave velocity at the bottom and side of the foundation on the static stiffness are significant and the static stiffness at analysis Case C and D are larger than that of Case A and B. This tendency can be seen both for swaying and rocking components while that of the rocking stiffness is more conspicuous than that of swaying component because of the effects of the foundation ends.

The real parts of the impedance at analysis Case C and D are significantly influenced by additional mass and decreases as low as that of Case A and B at non-dimensional frequency of 0.7 for the swaying component and 1.5 for rocking component.

The imaginary parts of the swaying and rocking components at analysis Case C and D are as a whole larger than that of Case A and B reflecting the contribution of damping material installed around the foundation.

The equivalent damping constant at analysis Case C and D estimated from swaying and rocking impedances are larger than that of A and B. This tendency is more conspicuous in the rocking component. This means that the damping material installed around the foundation is more effective in decreasing the rotational response component of foundation.

Superstructure responses. Response magnification factors of the superstructure model mass 2, 4 and 6 against free field ground are shown in Fig. 4. The response magnification factors of the superstructure of analysis Case C and D, with a damping material around the foundation, are obviously smaller than that of Case A and B. The reduction is as low as 10 to 30 percent exhibiting the contribution of the damping material.

DAMPING EFFECTS DURING SHAKING EXPERIMENT AND SEISMIC OBSERVATION

Seismic damping capability of building can be improved when the damping material is installed around the foundation as shown in the previous sections. On the basis of this result, a shaking table test was performed to verify the dynamic response under variable foundation surrounding using small foundation blocks, which were subjected to the subsequent seismic observation.

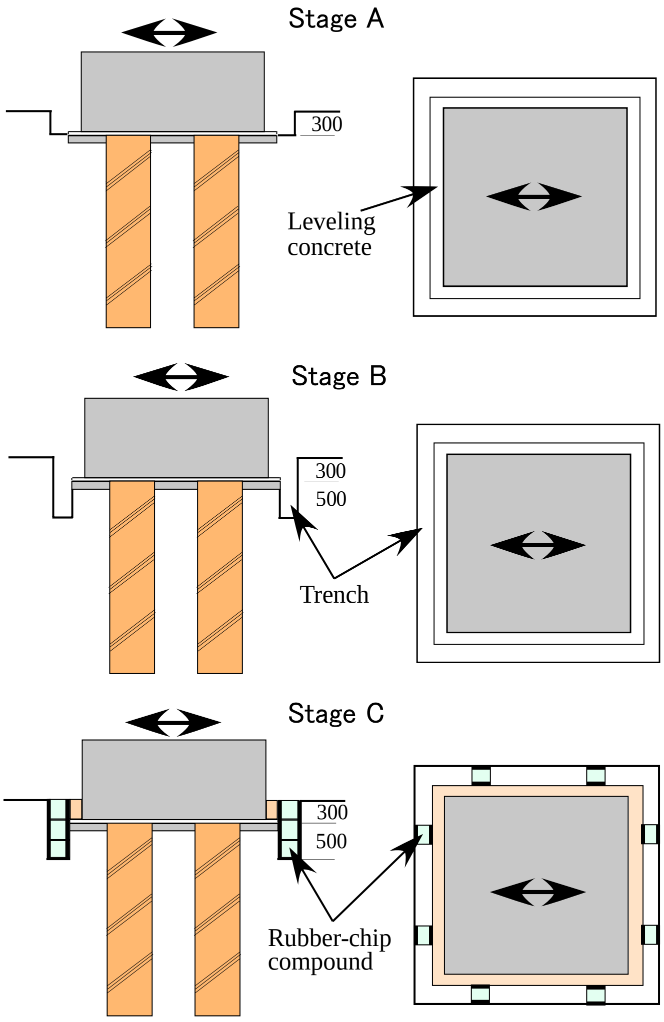


Fig. 8 Shaking test of foundation blocks with changes around foundations

Experimental Site

The experimental site is shown in Fig. 5. The foundation blocks A and B were built at an interval of one year with the same specification. Distance between foundation blocks A and B was 6m. Each foundation block was supported by four columns of soil-cement based improved ground with a diameter of 600mm. Details of the foundation block are shown in Fig. 6. The soil boring log of the experimental site is shown in Fig. 7. The soil layer composed of partial backfill layer of 0.1m thick, Kanto loam layer up to 2.8m deep, clay layer from GL-2.8m to -3.5m, fine tuff-sand layer from GL -3.5m to -5.3m and silty fine sand of deeper layers

The improved ground columns were 2.8m in length. N-value of the loam and clay layers was smaller than 5. Close to the experimental site, a base-isolated structure has been built and a seismograph has been installed 38m beneath the structure. The foundation blocks were used also for another experimental research project that will be reported elsewhere.

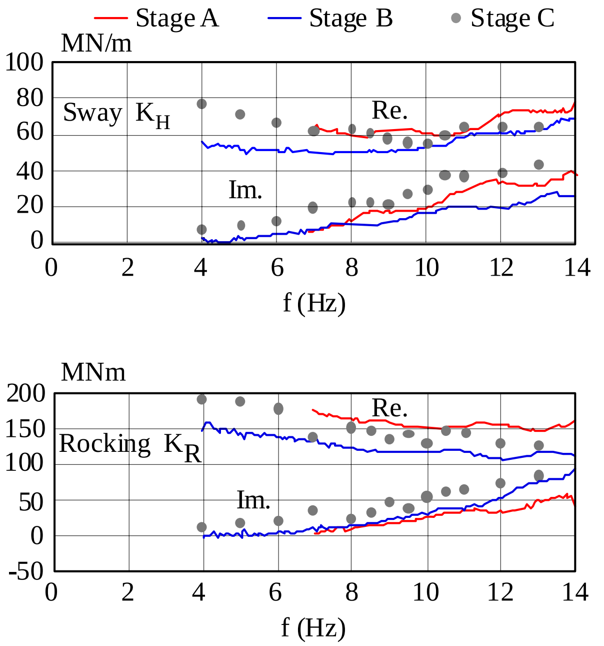


Fig. 9 Inversely calculated spring

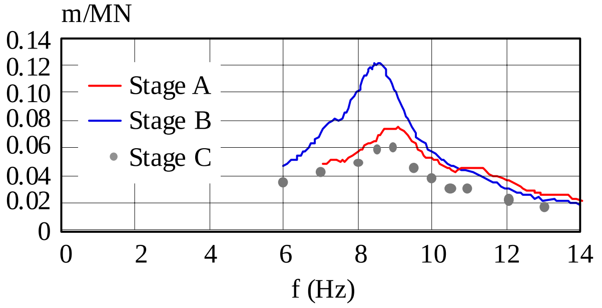


Fig. 10 Shaking direction at the top of the foundation blocks

Table 4 Observed seismic waveforms

No.	Date & hour	Center	Magnitude	Depth	Intensity
1	23 Oct. 17:56	Chuetsu	6.8	13 km	II (III)
2	23 Oct. 18:04	Chuetsu	6.3	9 km	II
3	23 Oct. 18:12	Chuetsu	6.0	12 km	II
4	23 Oct. 18:35	Chuetsu	6.5	14 km	II
5	27 Oct. 10:41	Chuetsu	6.1	12 km	II

Shaking Experiments

The shaking table was an eccentric mass type with a frequency range from 0.2Hz to 20Hz and the maximum shaking force of 30kN. Trenches around the foundation are shown in Fig. 8. Stage A is the original foundation with a peripheral trench of 0.22m wide and 0.3m deep excluding leveling concrete. Stage B has a deeper trench with an additional depth of 0.5m from the bottom of the leveling concrete. Stage C has a wider trench with a width of 0.32m and with two damper materials embedded at each side of the foundation The damper material was a diameter with a ceramics fiber which is a commercial product and different from that developed in this study.

Targeted resonance frequency of the specimen was 10Hz designed to be within the vibration range of the shaking table. Tests were performed in a low and mid progressive sweeping vibration mode. Test Stage A (7-15Hz) and B (4-14Hz) were subjected to progressive sweep vibration while test Stage C was shaken with an incremental stepping vibration of 0.5Hz around the resonance frequency range and 1Hz for the rest of frequency region.

After the shaking test, trenches of the foundation blocks A was filled with soil and compacted with a rammer while that of the foundation blocks B was filled with the damping material composed of asphalt-gravel-rubber chip composite for the subsequent seismic observation.

Result and Discussion

Change in dynamic response characteristics of foundation. Real and imaginary parts of the swaying spring of Stage B foundation, estimated from inversely calculated spring as shown in Fig. 9, appeared to be decreased compared to Stage A while no significant difference in the imaginary part of the rocking spring was found.

Resonance curves of acceleration response along with shaking direction at the top of the foundation blocks of Stage A, B and C are shown in Fig. 10. The resonance frequency of the Stage B foundation decreased as low as 8.5Hz by the trench contribution while that of Stage A and C foundation was approximately 9 Hz. Foundation Stage C with a damper using rubber chips form waste tires showed the lowest response. It is thus confirmed that the maximum displacement of foundation Stage A and C, with soil or damper around foundation, decreased more than that of foundation Stage B without anything in the trench, implying the effectiveness of the damper material.

Seismic observation. Seismic waveforms of Niigata-Chuetsu earthquake in 2004 were recorded as shown in Table 4. Among the waveforms observed at the top of the foundation blocks A and B, X-direction of the main waveform (No.1) is shown in Fig. 11. Using five observed waveforms including those of aftershocks, the waveforms observed at the top of the foundation

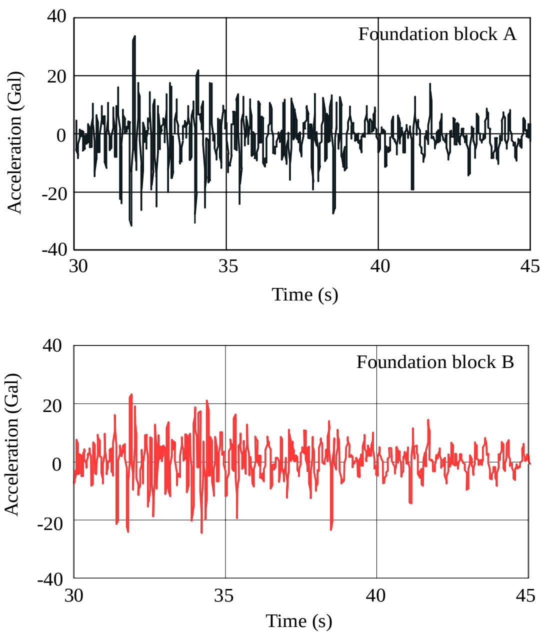


Fig. 11 Main waveform of Niigata-Chuetsu earthquake

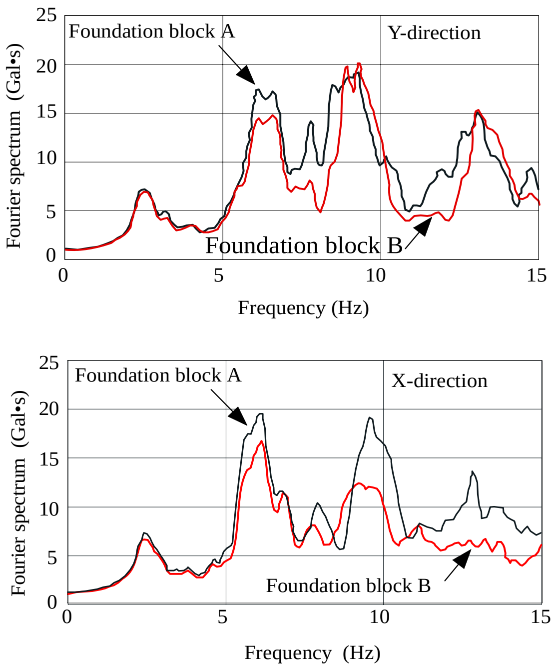


Fig. 12 Averaged Fourier Spectra

blocks are normalized with those at GL-38m and averaged Fourier spectrum are shown in Fig. 12. The maximum acceleration at foundation block A was 33.1gal while that of B was 25.8 gal, hence the seismic response of the foundation block B is smaller than that of A. It was also shown that the 3^{rd} order characteristic frequency of near-surface ground was close to the first order characteristic frequency of foundation-ground system and at this frequency range, transmittance of X-direction component of the foundation.

DEVELOPMENT OF A SEISMIC DAMPING MATERIAL COMPRISING INDUSTRIAL WASTES AND ASPHALT

As we have seen, installation of a damper material around building foundation is effective in lowering seismic response. With this finding, the authors developed such damper material especially using waste materials. One of the major components of the damper was a wood-chip, a by-product of timber demolition, of which those with an aspect ratio ranging from 4 to 25 were used. Rubber-chip was a crushed small particle of waste tires. Recycled fine powder was a residue of recycled fine aggregate production of which those with a particle diameter less than 5 mm were used. Among the waste materials, recycling rate of wood-chip is approximately 68% and rubber-chip is approximately 18% while that of recycled fine powder is in fact almost zero. Other components are a commercial silica powder and clay form Kasaoka area in Japan. Binder materials are an emulsified asphalt and water that is necessary for solidifying asphalt.

Experimental Methods

Materials used. Materials comprising the damper material are listed in Table 5 where symbols of each material are also shown. For instance, WC is for the wood-chip and RF for the recycled fine powder. Emulsifier was a nonionic type and solidifies at normal temperatures. The possibility of simplifying the site work is a major reason of adoption.

Mix proportions. Description of experiments and mix proportions of materials are shown in Table 6. The dosage of binder asphalt was 38ml (approx. 50g) per specimen with a diameter of 5cm and height of 10cm (ϕ50xh100).

Specimens. In preparing specimens, all the mixings were performed by hand. First, wood-chip and admixture were premixed and asphalt emulsion and water were mixed separately. Two mixes were then combined and mixed for three minutes.
Using a metal form with a dimension of ϕ–50mm x h-100mm, slurry was placed and compacted 10 times per layer. Numbers of specimens were two for each mix. After placing, specimens were air-cured in a thermostatic chamber with a temperature of 20°C and relative humidity of 60%.

Dynamic triaxial compression test. Dynamic triaxial compression was performed with testing machines of pneumatic and hydraulic pressure. Each test was performed according to the document, the Methods and Comments for Soil Tests specified by the Japan Geotechnical Society. Capacities of load cell were determined according to normal soil tests. Displacement gauges were a non-contact type to measure fine strains and a displacement transducer to measure large displacement. Initial restriction pressure was 30kPa assuming the maximum depth was as deep as 5m. Loading and loading rate was 1 to 2Hz for the seismic waves of unsaturated conditions, assuming that construction depth was shallower than the water table.

Table 5 Materials used

Material		Description	Role
Wood-chip	WC	Crushed timber with an aspect ratio of 4 to 25 and max. length of 40mm	Main admixture
Rubber-chip	TC	Chopped waste tire with max. diameter of 10mm	Admixture
Recycled fine powder	RF	Crushed concrete with a diameter less than 5mm	Admixture
Recycled fine aggregate	RA	Crushed concrete with a diameter of 10 to 20mm	Admixture
Silica sand	SS	A commercial product with a diameter of 0.07 to 0.6mm	Admixture
Kasaoka clay	KC	A commercial product with a conditioned particle diameter	Cover
Asphalt emulsion	EA	A nonionic emulsion solidifies at normal temperaures	Binder
Water	WT	Tap water	Binder

Table 6 Experiments of the damper material

Case	Experiment	Admixture	Binder composition	Curing period	Layer of compaction
1	Stress-strain relations with different amount of water added to asphalt emulsion	WC/RF=0.67/0.33	EA/WT=0.5/0.5 EA/WT=0.75/0.25	21	3
2	Relations between axial strain and elastic modulus or damping factor with different amount of recycled fine powder added to wood-chip	WC/RF=0.5/0.5 WC/RF=0.67/0.33	EA/WT=0.5/0.5	21	3
3	Relations between axial strain and elastic modulus or damping factor when various types of admixture are added to wood-chip	WC/TC=0.5/0.5 WC/RF=0.5/0.5 WC/SS=0.5/0.5 WC/RA=0.5/0.5	EA/WT=0.75/0.25	21	3
4	Relations between axial strain and elastic modulus or damping factor when curing period is different	WC/RF=0.67/0.33	EA/WT=0.85/0.15	14, 28	3
5	Relations between axial strain and elastic modulus or damping factor when number of compaction layer is different	WC/RF=0.33/0.67	EA/WT=0.85/0.15	28	2, 3, 5, 10

RESULT AND DISCUSSION

Effects of asphalt emulsion

Effects of mix proportion of asphalt emulsion and water, EA/WT, on the property of the damper device is shown in Fig. 13 in terms of stress strain relation. Admixture of this mix was wood-chip and recycled fine powder with a volume fraction of WC/RE=0.67/0.33. Volume fraction of asphalt emulsion and water of Fig.12 (A) and (b) were 0.5/0.5 and 0.75/0.25 respectively. It is shown in this figure that the case (A), rich in asphalt emulsion, exhibited larger elastic modulus E and damping factor h than those of case (B) with lower fraction of asphalt emulsion.

Effects of admixture composition

Relations of half amplitude of axial strain ε with equivalent elastic modulus E and damping factor h are collectively called in this study strain dependency, which is shown in Fig. 14 when admixture of WC+RF and EA/WT fraction of 0.75/0.25 were used. It can be seen in this figure that the strain dependency of equivalent elastic modulus E became larger when WC/RF fraction was 0.5/0.5 rather than 0.67/0.33. On the other hand, damping factor h showed no significant difference regardless of the WC/RF fractions and ranged from 15 to 26%.

Effects of type of admixture

Strain dependency of damper material with various admixtures is shown in Fig. 15. The major admixture was wood-chip and each one of the secondary admixture such as rubber-chip (TC), recycled fine aggregate (RA), recycled fine powder (RF), silica sand (SS) and mixture of recycled fine powder and blast furnace slag (RF+BS) were added. The damping factor h showed a large value when RF or SS were added while E and h became smaller when TC is added compared to the other admixtures.

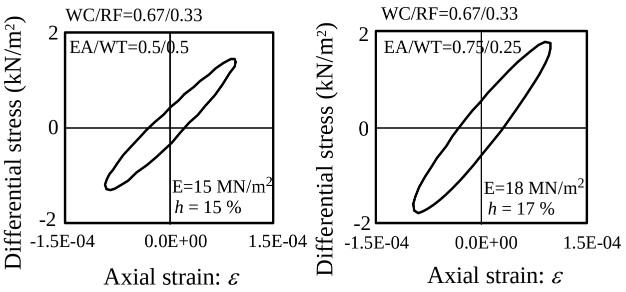


Fig. 13 Strain dependency with different asphalt/water fractions

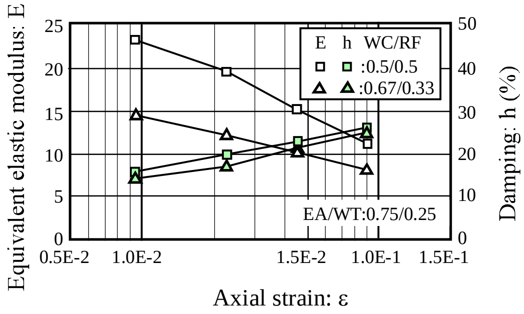


Fig. 14 Strain dependency with different admixture fractions

Effects of curing period

Effects of curing on the strain dependency are shown in Fig. 16. Admixture used was WC+RF and curing period was 14 and 28 days. Elastic modulus E increased slightly when curing period was extended from 14-day to 28-day while damping factor h remained unchanged. Hence the effect of curing period on the damping properties may be negligible.

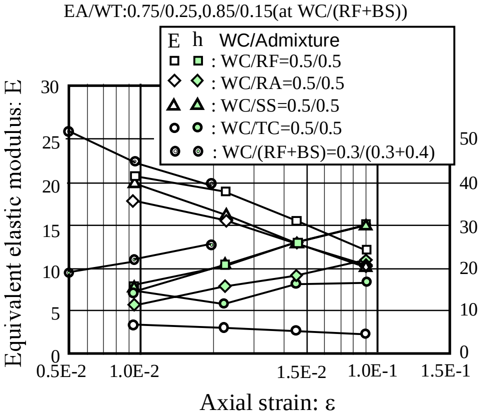


Fig. 15 Strain dependency by the type of admixture

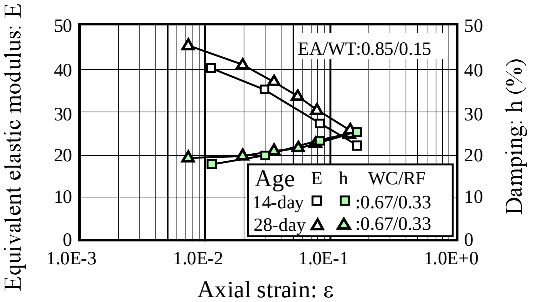


Fig. 16 Strain dependency with different admixture fractions

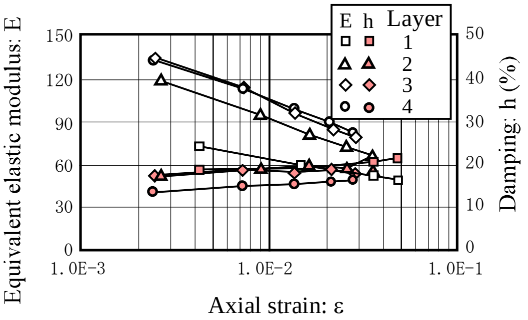


Fig. 17 Strain dependency with different compactions

Effects of compaction

Effects of compaction on the strain dependency are shown in Fig. 17. Admixture used was WC+RF and the number of compaction (number of placement layers in a mold) was varied. Elastic modulus E became extremely small and damping factor h became large when the number of layers was two. With an increase in number of compaction, Elastic modulus E increased and damping factor h remained unchanged except for the number of compaction of five.

These findings show that excellent damping material can be obtained when wood-chip (WC) and recycled fine powder (RF) are used as admixture, and control of curing period and number of compaction were found to be important.

CONCLUDING REMARKS

Analysis and experiments presented in this report can be summarized as follows.

(1) Seismic response analysis of proposed damper system applied to the full-scale structure has confirmed that the installation of damper around the foundation can reduce seismic response to the rocking component.

(2) Observed seismic waveforms has shown that the amplitudes of the maximum acceleration and Fourier-transformed spectrum of the foundation block B was 30 percent smaller than that of A. Expected damping effects were confirmed at an earthquake.

(3) Proposed damper material comprises construction and industrial wastes and a binder of asphalt emulsion. Study of its dynamic characteristics has confirmed that the proposed damper system is feasible.

(4) Damping effects increased with an increase in asphalt emulsion content.

(5) When recycled fine powder was used as an admixture of the damper material, a large stress dependency in elastic modulus and damping factors was observed compared with other admixture. When the recycled fine powder is used in larger amount than wood-chip, elastic modulus increased while damping factors showed no significant difference.

(6) When curing period extended over 14 to 28 days, elastic modulus showed slight increase while damping factors remained unchanged.

(7) When the number of compaction increased, elastic modulus showed an increase while damping factors remained unchanged.

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