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Cement and Soft Mud Mixing Technique Using Compressed Air-Mixture Pipeline: Efficient Solidification at a Disposal Site

Abstract

Dredging, conveyance, and disposal of the soft bottom mud have been greatly improved by various methods to achieve efficiency and environmental preservation. A compressed air-mixture conveyance system using a pipeline is one of the suitable methods for soft mud transfer from the dredging site to the disposal site. The method requires no excess water to assist the mud flow in the pipeline, eliminating turbid-water treatment installation at the disposal and reclamation sites. However, a long period is required for the wet and soft mud to become dry. To shorten the time required for drying, various compacting and drying methods have also been used. Mixing a solidifier like cement in the dredged mud is a solution but an expensive mixing plant is necessary.

The cement-mixing method using the compressed air-mixture pipeline for soft mud conveyance has been developed for effective and economical disposal work. This method uses plug flow generated in the pipeline with compressed-air assistance to mix cement-based solidifier with mud in the pipeline. Uniform cement mixing is achieved by injecting solidifier into an expander pipe with a larger diameter than the pipeline. This method will eliminate conventional mixing plants and will be more economical than other methods.

In July 1997, field tests of the new method were carried out by injecting 50 kg/m^3 and 70 kg/m^3 of solidifier in the expander pipe fitted to a 200 m^3/h capacity pipeline. Good test results showed that the method is applicable to actual operations. The outline of the new method and the field tests at the Ishinomaki reclamation site (Miyagi Prefecture) are described.

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Introduction

In modern Japan where development has been proceeding steadily, both large urban centers and smaller cities have had the serious problem of dealing with reclaimed soft mud at disposal sites. The method of soft mud reutilisation through addition of a solidifier has come into wide use. In general, the solidification disposal method involves the use of a barge mounting a special mixer. However, the barge is equipped with high-grade systems to undertake a variety of tasks, so cost is a major stumbling block for use only at reclamation sites. Therefore, a new method was required to yield a large amount of reclamation-strength end product in a short time through utilisation of facilities with highly efficient mixing characteristics.

The technique described here is the solidifier (cement) and soft mud mixture technique that uses the compressed air-mixture pipeline to take advantage of the characteristics of plug flow during compressed air transfer, allowing direct introduction of the solidifier into the soft mud during transport, for full utilisation of the transfer action.

This paper describes the solidification disposal method, the theory behind the cement and soft mud mixture technique using the compressed air-mixture pipeline, and the results of limited and full trials using this technique.

BACKGROUND TO TECHNOLOGICAL DEVELOPMENT

Environmental problem

From the latter half of the 1950s, the high rate of economic growth caused a persistent shortage of land sites in waterfront areas that formed the basis of economic activities. As Japan lacks both land and

resources in general, dredging and land reclamation were undertaken as national projects to meet the need for more space.
The conventional reclamation method at the time involved surrounding the area to be reclaimed with steel or concrete, then using suction dredgers to transfer the soil. More than a sixth of Tokyo Bay was thus reclaimed, drastically altering the coastline. This reclamation method made possible the creation of modern industrial Japan through the provision of waterfront industrial sites.

In the 1970s, the environmental problems involving inland sea areas such as the Seto Inland Sea and the "Big Three" bays (Tokyo, Osaka and Ise Bays) became serious enough to require urgent action for preservation of the environment. In addition to improvement of the drainage system and waste water disposal methods, the dredging of soft mud from the bay areas became essential. However, soft mud is not suitable for use as reclamation material, so it had to be dumped offshore.

Subsequent global environmental concerns led to a close examination of the effect of offshore dumping on marine organisms and the conclusion that there should be limitations placed on such dumping, so soft mud became very difficult to dump.

As offshore dumping became impossible, the only available method of disposing soft mud was to find suitable disposal sites, a very difficult task in Japan where such sites are quite difficult to locate, and so these are resources which need to be utilised most effectively. Therefore, the use of grab bucket dredgers that enable the collection of mud maintained in its near-original condition, rather than suction dredgers, became the preferred barge for dredging operations.
These social requirements led to the development of grab bucket dredgers to transfer mud in near-original conditions through use of the compressed air-mixture pipeline.

Compressed air-mixture transfer method

When pipeline transfer of grab-bucket dredged mud in near-original conditions is attempted through use of conventional suction pump equipment, the large amount of friction produced within the pipeline prevents transfer of the material over a long distance. Long-distance transfer of such material generally requires dilution with water or other fluid to deal with the friction problem. However, dilution increases the dredged mud volume, making it difficult to find enough space at the disposal site.

In contrast, mixing of grab bucket dredged mud with compressed air of very low or negligible friction reduces the entire friction to enable long-distance pipeline transfer.

Akinori Sakamoto (left), receiving the IADC Award from Mr Peter Hamburger, IADC Secretary General, at the closing ceremonies of WODCON XV.

IADC Award 1998

Presented during the WODCON XV,
Las Vegas, Nevada, USA
June 28-July 2, 1998

At the 15th WODCON held in Las Vegas, Nevada, USA, from June 28-July 2, 1998, Mr Akinori Sakamoto was presented with the annual IADC Award for young authors. Mr Sakamoto graduated from the Applied Chemical Department of Muroran Institute of Technology in March 1994 where he studied Chemical Plant Engineering. He then joined the Machinery and Electric Department of Toa Corporation, Tokyo, Japan, as a mechanical engineer, where he now specialises in reclaimed land solidification engineering.

Each year at a selected conference, the International Association of Dredging Companies grants an award to a paper written by a young author. The Paper Committee of the conference is asked to recommend an author who is younger than 35 years of age and whose paper makes a significant contribution to the literature on dredging and related fields.The purpose of the award is "to stimulate the promotion of new ideas and encourage younger men and women in the dredging industry". The IADC Award consists of US$1,000, a certificate of recognition and publication in *Terra et Aqua.*

This method has promoted the effective use of disposal sites and allows long-distance transfer of dredged mud in large amounts, so many compressed-air transfer pipeline systems have been built.

Nevertheless, reclamation by this method still requires some extra water to be removed, so foundation work is needed at the disposal site prior to receiving the mud. Moreover, disposal sites in waterfront areas have limitations on noise and vibration owing to the change in the surrounding environment since reclamation work was first started.

Therefore, the solidification method for mixing the dredged mud and solidifier to achieve solidification before disposal has been developed.

OUTLINE OF SOLIDIFICATION DISPOSAL

Solidification disposal is one of the new foundation modification methods, and involves the mixing of dredged mud conveyed by grab bucket and a solidifier. The amount of the solidifier can be adjusted to ensure the end product matches the requirements, so materials of various characteristics can be provided for use according to application.
This method has advantages, compared with the conventional method of modifying the reclaimed soft mud such as no extra foundation work required on site.

The objectives of solidification disposal are the following:

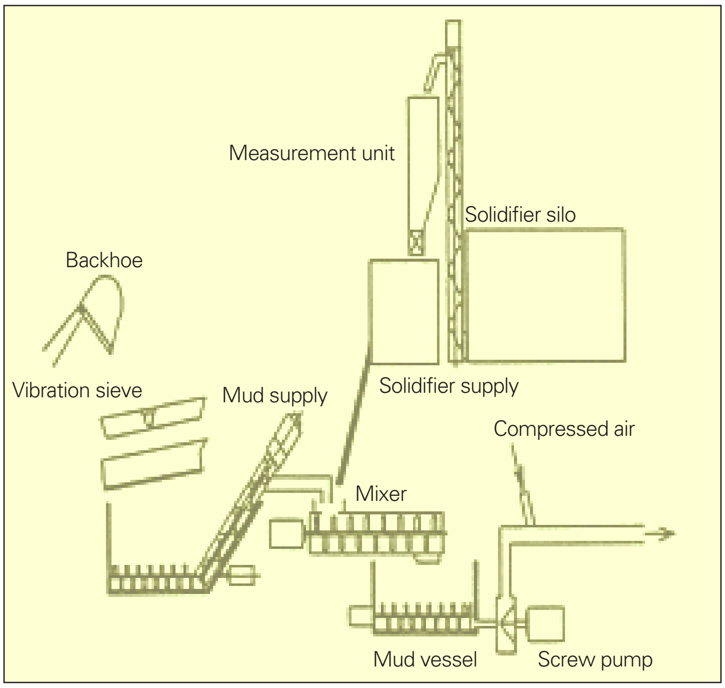


Figure 1. Schematic drawing of process flow.

- prevention of outflow of dredged mud from the disposal site to non-disposal site areas;
- promotion of adequate strength of solidified dredged mud to prevent damage to the operation of heavy machinery involved in the disposal work;
- promotion of reuse of dredged mud as reclamation and foundation work soil by modifying the dredged mud into solidified form; and

Figure 2. Solidifier mixing plant barge.

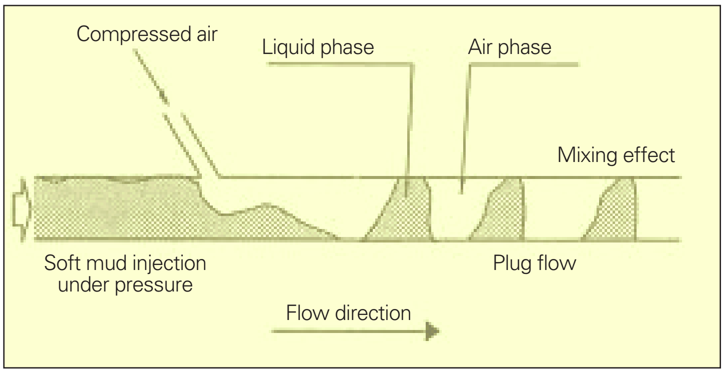


Figure 3. Two phase flow of air and liquid.

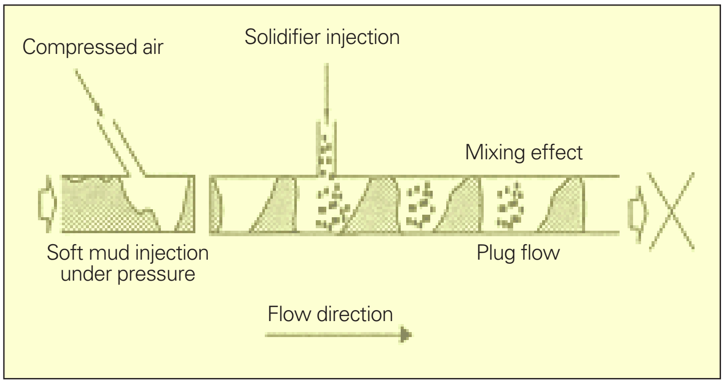
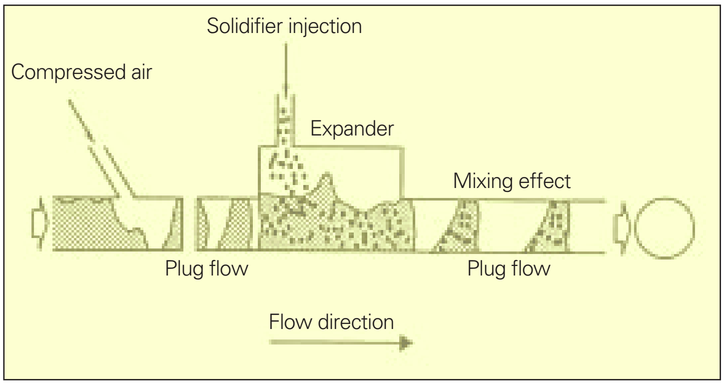


Figure 4. Solidifier injection mechanism 1.

Figure 5. Solidifier injection mechanism 2.



– enhancement of subsequent foundation work on the site after modification, making the land more quickly available for use.

The construction of the Kansai International Airport in Osaka Bay and others shows that recent ports and harbours development in Japan has become larger in scale, requiring huge amounts of soil and sand for reclamation. However, there are few sources of these materials available near coastal land.

Solidification disposal is therefore becoming an essential technique amongst other promising techniques for the future effective utilisation of dredged mud, because of elimination of additional foundation work subsequent to reclamation while allowing handling of large amounts of modified dredged mud.

Solidification disposal method

Most solidification disposal work in port, harbour and waterfront areas involves the use of a special solidifier mixing barge. As an example, an overview of this type of barge with 200 m^3/h handling capacity and the systematic workings of this vessel is provided in Figure 1.

The system mainly consists of the following four components:

1. *Unloading section*
   Dredged mud is unloaded using the backhoe for discharge into the hopper. Potentially harmful items like rocks and wooden materials are removed using vibration sieves. The mud is stored in the mud vessel below the sieve, and an agitator installed in the vessel constantly supplies the mud to the mixing plant which fluidises the mud by the screw feeder.
2. *Solidifier section*
   The solidifier is supplied by the screwfeeder to the mixer in amounts measured by loadcells. The supply of solidifier can be adjusted to meet the solidification purpose.
3. *Mixing section*
   The dredged mud and the solidifier are mixed uniformly by a double-axis paddle mixer. The mixer is the tilting type, and the time necessary for mixing is also controllable.
4. *Compressed-air transfer section*
   The mixed modified soil is stored in the vessel and supplied to the pressurised pump unit by the screwfeeder to be pumped out through the transfer pipeline to the disposal site. Generally, the addition of the solidifier increases the friction within the pipeline and thus limits the transfer distance to about 200 m.

Currently, several such special-purpose barges are in operation in Japan to supply material for land reclamation, or to prevent leakage of pollutants from industrial waste at the disposal site (Figure 2). These activities require the operator to provide quality assurance, resulting in relatively higher operational costs owing to the complications in system structure.

Cost is definitely the limiting factor preventing wider use for reclamation. Moreover, the recent Japanese economic consideration has required better control of operational costs even for non-major works, especially when the costly plant barges are involved.

The newly developed solidifier mixing system using the compressed-air transfer pipeline can be used to realise low-cost solidification disposal in large quantities even in combination with the currently-used compressed-air transfer systems. The new method can achieve disposal at low cost.

OUTLINE OF NEW SOLIDIFIER MIXING SYSTEM USING COMPRESSED-AIR TRANSFER PIPELINE

Outline of development

Development of the new solidification disposal method required easy bulk disposal at low cost. The turbulence effect of the plug flow during compressed air-mixture transfer in the pipeline was investigated and the basic concept of mixing the solidifier and soft mud was developed.

The main items for consideration were:

- use of the turbulence effect of the plug flow; and
- establishment of a mechanism and system for directly adding the solidifier during conveyance in the pipeline.

Experiments showed that the addition of the solidifier via the compressed air inlet was adequate for the mixing effect. However, with this method, there is a limitation to the transfer distance as with the mixing plant barge method, thus making long-distance transfer difficult. A mechanism was required for adding the solidifier into the plug flow within the pipeline to achieve long-distance transfer.

Theory of the method

Mixing theory

When compressed air is injected into the pipeline during the transfer of soft mud, the two-phase flow of air and liquid is formed as shown in Figure 3. The liquid phase part (or plug flow) moves in the turbulent flow in the pipe, and a mixing effect is expected. The new mixing system uses the effect of plug flow to mix the solidifier in the pressurised pipeline.

Solidifier mixing mechanism

When the solidifier is directly injected into the compressed-air transfer pipeline to mix with soft mud, the solidifier concentrates at the air-phase parts, and no uniform mixing of materials can be expected as in Figure 4. This was confirmed by tests in the past. Based on various experiments, a new mixing system was developed as shown in Figure 5, in which the expansion pipe (the expander) with a larger diameter than the transfer pipeline diameter was inserted midway through the pipeline.

The plug flow in the pipeline is disturbed in the expander, and becomes a wave-like flow. This allows addition of the solidifier to the soft mud. Soft mud and solidifier flow in the smaller diameter pipeline at end of the expander tail, and plug flow is formed again to mix the solidifier with the soft mud. The new mixing system is applicable to distances of up to 3,000 m, which is the maximum transfer length of the compressed-air transfer system. The special-purpose mixing plant barge cannot be applied to this transfer distance.

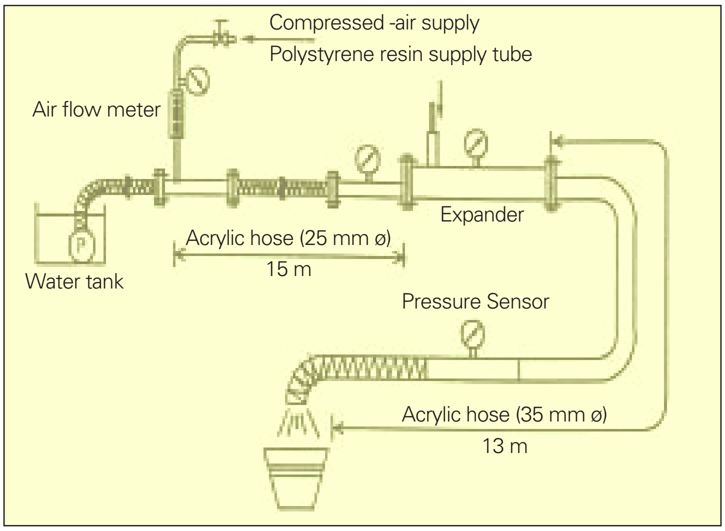
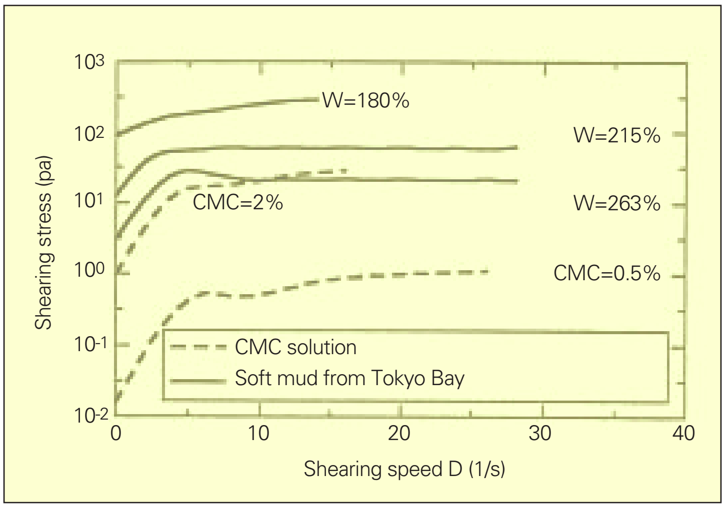


Figure 6. Scale model test configuration.

Figure 7. Fluidity characteristics of CMC solution.



The essential engineering points are appropriate diameter and length of the expander. To establish the engineering technique, scale model tests were conducted to clarify the behaviour of the plug flow for development of the expander.

SCALE MODEL TESTS

Test method

Tests were carried out using a one-tenth scale model of the actual system. The scale model configuration is shown in Figure 6. The compressed-air transfer pipeline

Table I. Test conditions: with and without expansion pipe.

Test	Compressed-air pipe (mm)	Expansion pipe (mm)		Compressed-air pipe (mm)	CMC concentration %
	Pipe diameter d1	Pipe diameter d2	Pipe length L	Pipe diameter d3	
1	25	25	300	35	2
2	25	50 - 100	300 - 1,000	35	2

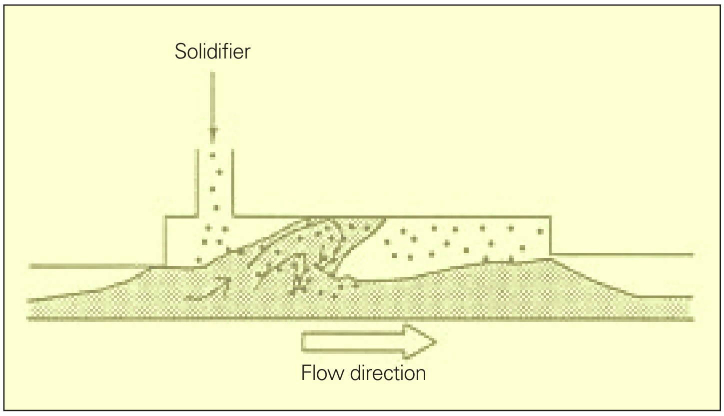


Figure 8. Separating turbulence by rapid expansion.

Figure 9. Contraction turbulence.

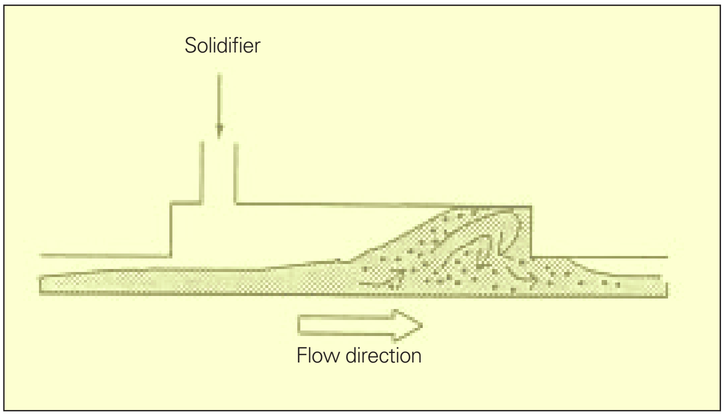
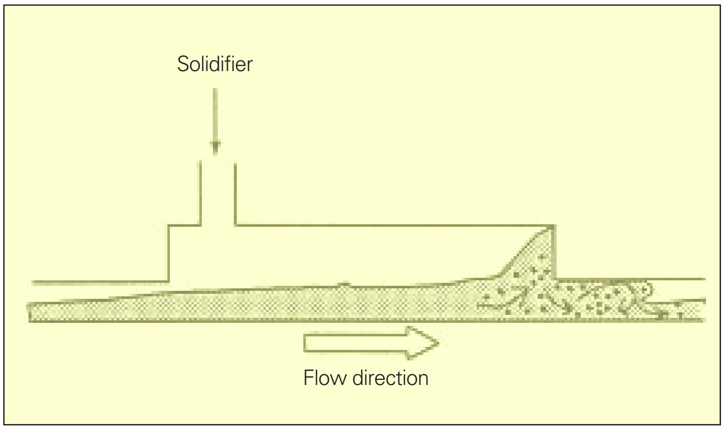


Figure 10. Turbulence owing to recycled plug.



was a 15 m long acrylic hose with an inner diameter of 25 mm, with the expansion pipe at the end. The other end of the expander was joined to a 13 m long acrylic hose with an inner diameter of 35 mm. The model material was carboxy methyl cellulose (CMC) solution used as a substitute for the dredged material, as CMC has similar fluidity to the dredged material and is convenient to handle in testing as it is colorless and transparent.

Figure 7 shows the results of measuring the fluidity curve of CMC solution. The measurement was carried out with a revolving viscosity meter. The slope of the fluidity curve is the virtual viscosity of the fluid.
The solid line in the figure shows changes in values measured by altering the water content ratio in the soft mud collected from the seabottom in Tokyo Bay, and the dashed line is obtained by changing the CMC concentration. A water solution of 2% CMC was used in the tests.

Tests were conducted for the two cases shown in Table I: Experiment 1 without the expander and Experiment 2 with the expander. Two cases were compared for behaviour of the plug flow. Several expanders with different diameter and length were prepared for testing this key component of the system. Polystyrene resin particles were used as the solidifier substitute, which were input into the expander from the upper part, and the behaviour of the resin particles was observed visually.

Test results

Mixing process observation discovered two cases, of good and poor mixing, resulting from differences in the diameter and length of the expander. The following effects of the expander were obtained from the scale model tests.

Plug flow behaviour

Plug flow behaviour in the expander found in the basic experiments is shown below. The effects of three types of turbulent flows were confirmed when mixing the solidifier into the plug flow using the expander:

1. Separating turbulence by rapid expansion: Plug separation turbulence induced by rapid expansion in

the cross sectional direction as shown in Figure 8;

2. Contraction turbulence: Turbulence induced by rapid contraction as shown in Figure 9.
3. Turbulence owing to recycled plug: Turbulence generated when a plug is recycled as shown in Figure 10.

Blockage prevention effect

The solidifier powder must be injected by compressed air into the expander, and the supply port may be blocked by adhesion of solidifier when the port becomes wet. Therefore, the supply port was located at the upstream side of the expander, where the plug flow separates from the upper wall of the expansion pipe owing to rapid expansion. This provides an air pocket around the solidifier supply port, preventing blockage of the supply port Figure 11.

Expansion pipe size and mixing ratio

The mixing ratio was assessed in three stages when resin particles were input, and the diameter ratio (d1/d2) of the expander of the compressed-air transfer pipe length and the diameter ratio (L/d2) of the expander of the expander length were also studied.

The results are shown in Figures 12 and 13.

Figure 12 shows an adequate mixing effect is attained when the expansion diameter is two to three times larger than that of the compressed-air transfer pipe. Figure 13 shows an adequate mixing effect is achieved when the expander length is six to fourteen times larger than the expander diameter.

Adoption of test results for design

Based on these results, the expander design and application to the compressed-air transfer pipeline were conducted.
The diameter of the expander was fixed as two to three times larger than that of the compressed-air transfer pipeline, and the length of the expander was six to fourteen times larger than the diameter of the expander.

Based on these design criteria, a prototype expander was designed and fabricated for field verification tests (Figure 14).

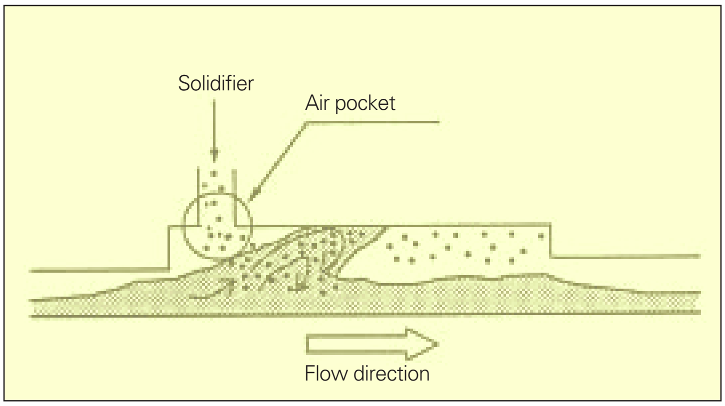


Figure 11. Supply port location.

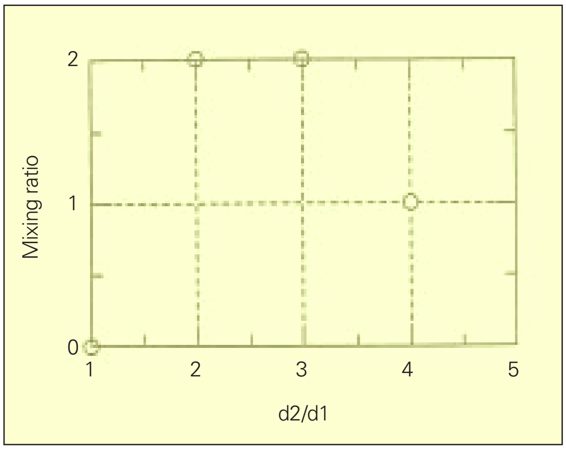


Figure 12. Expander diameter and mixing ratio.

Figure 13. Expander length and mixing ratio.

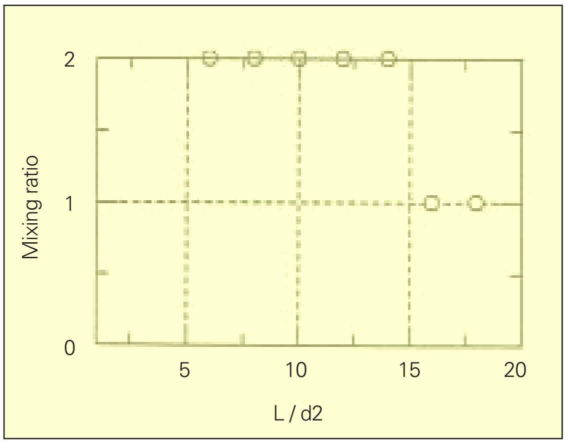


Table II. Test specifications with expansion pipes based on scale model tests.

	Treatment (m^3/h)	Pipeline capacity (mm)	Expansion pipe (mm)		Volume of solidifier (kg/m^3)	
		dl	diameter	pipe length		
1996	60	250	500	5,500	50	75
1997	180	400	800	4,800	50	75
	230				50	

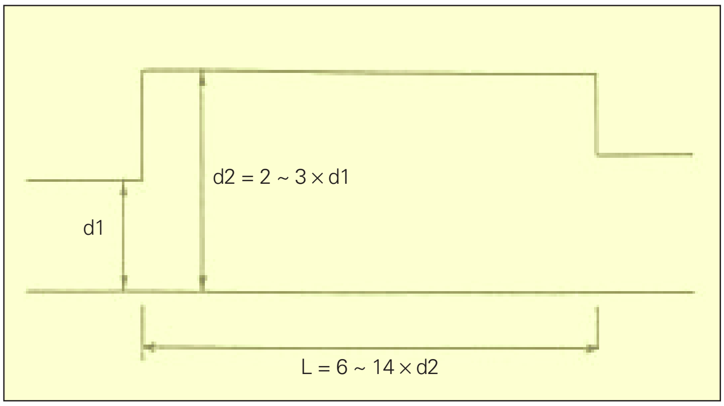


Figure 14. Design criteria for expander.

Figure 15. Test field.

VERIFICATION TESTS

Testing outline

A test field was provided for verification at an actual reclamation site where solidification work was carried out (Figures 15 and 16). Tests were conducted on the system at a capacity of 60 m^3 in 1996 and 200 m^3 in 1997. The strength of solidified soil was targeted at 200 kN/m^2 measured as unconfined compression strength.

Test method

Based on the results obtained from scale model tests, actual scale tests were carried out using plug flow generated in the pipline with and expander to confirm the uniform mixing soilidifier and mud is possible.
The test equipment is outlined in Figure 17.
Tests were carried out as follows. Dredged mud was first sent to the expander at a distance of 100 m, where the solidifier was injected for mixing with mud. The mixture of solidifier and mud was then transferred in a pipeline with a smaller diameter than the expander to be discharged from the cyclone suppressor attached at the pipeline end. The mixture discharged was cured for about one month in a pit in the test field.

Test conditions

1. Test specifications
   The expander was based on the design obtained from scale model tests (Figures 18 and 19).
   Test specifications including expander dimensions are shown in Table II.

Figure 16. Discharge of solidifier and mud mixture.

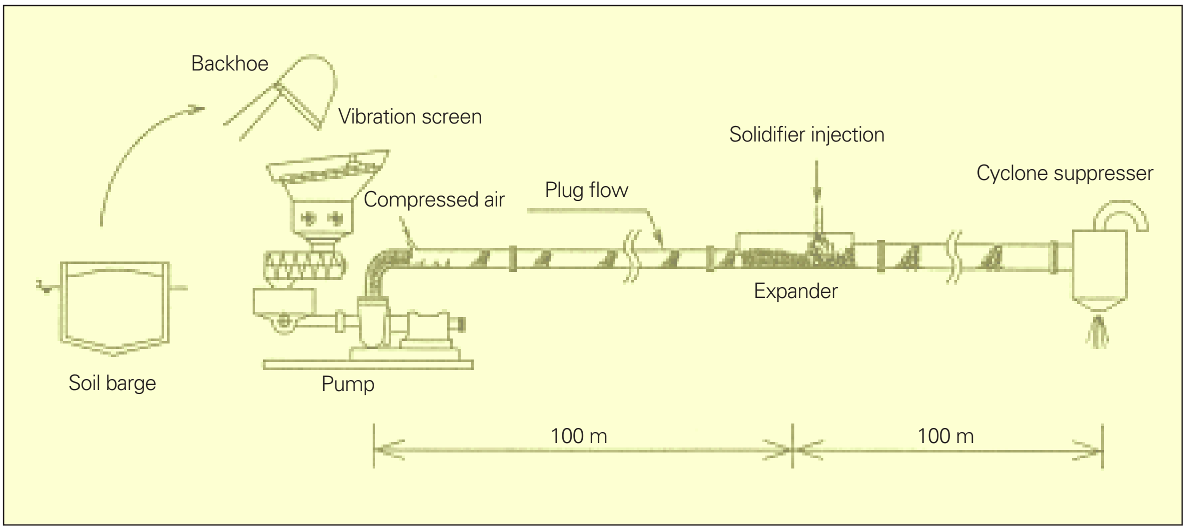


Figure 17. Test installations.

Figure 18. Expander (60 m^3/h).

Figure 19. Expander (200 m^3/h).

2. Dredged mud
   Dredged mud to be modified was provided by a grab bucket dredger. The mud was transported by a soil barge. Table III gives average values obtained from physical tests on the dredged mud that was used for field tests.

3. Evaluation method of solidified mud
   Various evaluation methods have been used to assess the soil nature. In Japan, modified mud is generally assessed by the unconfined compression strength test. In our tests, the unconfined compression strength and cone penetration tests were used for evaluation of modified mud characteristics.
   The cone penetration tests can be applied to modi-

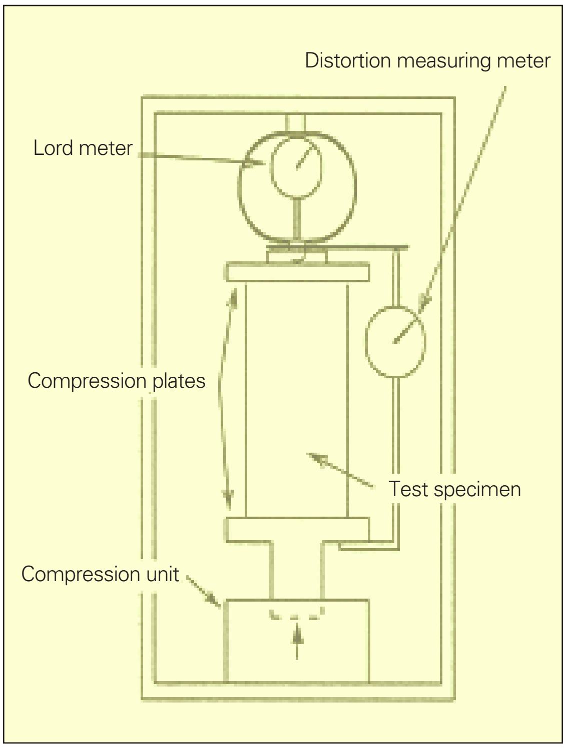


Figure 20. Unconfined compression strength tester.

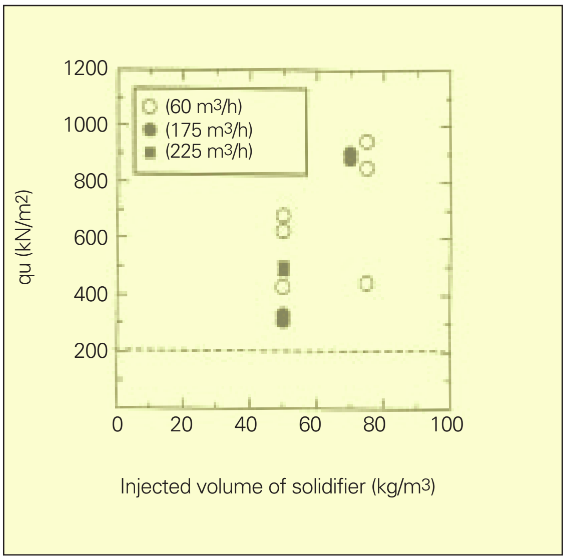


Figure 21. Solidifier injection volume and unconfined compression strength.

fied mud before solidification, allowing continuous evaluation. This cone penetration test method is an effective measure to control the quality of soil ground.

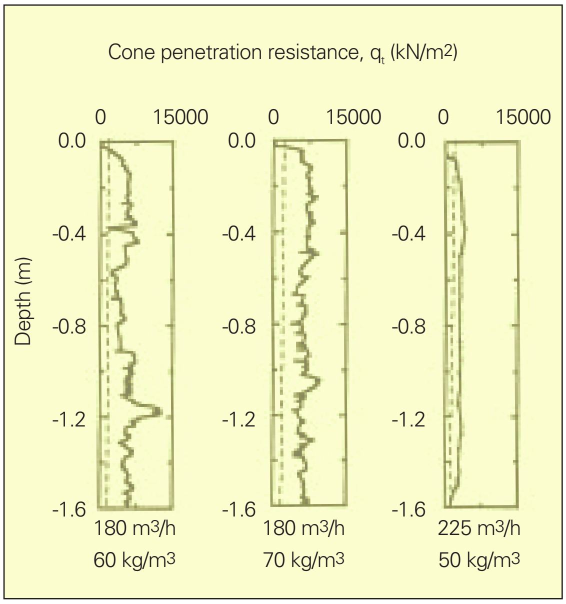
(a) Unconfined compression strength test
The unconfined compression strength test is used to assess the modification effectiveness and of 1% per minute in continuous compression is used for testing the specimen. By measuring the maximum stress under this method, the compression strength of modified mud can be obtained.
The test is conducted on a test specimen measuring 50 mm in diameter and 100 mm in length in the standing position. The test criterion is based on the distortion ratio: a distortion generation of 1% per minute in continuous compression is used for testing the specimen. By measuring the maximum stress under this method, the compression strength of modified mud can be obtained. The testing device is shown in Figure 20.

Table III. Average values of physical test results of dredged mud.

Test items			1996	1997
General				
	Initial water content ratio	w (%)	187.3	171.1
	Wet volume	ρ t (g/cm3)	1.278	—
	Soil particle density	ρ t (g/cm3)	2.691	2.613
	Soil pH values	Li (%)	10.5	7.8
Particle characteristics				
	Gravel	(%)	0	2
	Sand	(%)	3.7	17
	Silt	(%)	39.6	35
	Clay	(%)	56.7	46
	Max. Particle size	(mm)	0.486	5.03
Consistency characteristics				
	Viscosity limit	WL (%)	176.2	148.1
	Plasticity limit	WP (%)	65.5	36.4
	Plasticity index	IP (%)	111.9	117

Figure 22. Collected test specimens.

Figure 23. Cone penetration resistance and distribution by depth.



(b) Cone penetration test

The cone penetration test is achieved by measuring penetration resistance values when the cone rod is inserted into the soil ground. In the field test of 60 m^3/h capacity, portable cone penetration tests were carried out but penetration was impossible at part of the test field area. Based on this experience, electrically-driven cone penetration tests were carried out for the 200 m^3/h capacity, using the improved type of the conventional tester with a cone tip angle is 60° with a cross-sectional area of 10 cm^2. The latter situation is described here.

Test results

1. Unconfined compression strength test results

Figure 21 shows the relationship between the solidifier volume used and unconfined compression strength of modified mud, which were obtained from the field tests. The test specimen was collected by boring into modified soil ground, which was cured for one month after placement. Figure 22 shows the collected test specimens. All test specimens satisfied the target value of 200 kN/m^2.

2. Cone penetration test results

The relationship between unconfined compression strength and cone penetration resistance is expressed as follows:

$$qt = 20 \times (qu/2) \qquad (1)$$

where,

qt: Cone penetration resistance (kN/m^3, after pore water pressure compensation)

qu: Unconfined compression strength (kN/m^3)

Figure 23 shows the distribution of cone penetration resistance values by depths. The dotted line in the figure indicates the targeted strength for soil modification, which was obtained by converting into qt values using equation (1). The soil strength over all the modified soil ground area met the target value for modification. Moreover, the modified soil quality in the depth direction was comparatively uniform. Figure 24 shows the cone penetration tests being performed.

3. Conclusions based on verification tests

Use of the expander based on basic R&D enabled mixing of the solidifier during transfer of soft mud by plug flow in the pipeline. The mixing effect in the expander by plug flow was confirmed together with

Table IV. Economic comparison between mixing plant barge and new system.

	Mechanical mixing method	New mixing system	Remarks
Solidification costs	1	0.75	Including service ships
Solidifier volume	1	1.20	
Total costs	1	0.84	

Figure 24. Cone penetration test being performed.

the applicability of the mixing system to actual construction. The quality of the modified mud was satisfactory, meeting the target strength, and the quality in the depth direction was uniform.

The principle of the construction method can cope with requirements for greater treatment capacity by using an expander with a larger diameter. At present, soft-mud transfer vessels with compressed air-mixture pipelines range from 600 to 1,000 m^3/h capacity in Japan. Combined with such transfer vessels, the new solidifier mixing system will greatly facilitate large land area reclamation, and great economy can be expected.

Cost Comparison

The new solidifier mixing system was compared with a mixing plant barge with a mixing capacity of 200 mm^3/h. The comparison included the costs required for equipment operation including equipment rental fee, personnel expenditures, fuel cost, and material costs to achieve unloading of dredged material and transfer to discharge at a disposal site. The cost comparison is shown in Table IV, in which the index of 1 is for the mixing plant barge. However, consumption of the solidifier, as the new solidifier mixing system does not use any measuring control system, assumed 20% premium consumption for the new system against that of the mixing plant barge.

The cost comparison shows the total construction costs were reduced by about 15% compared with the conventional mixing plant barge. Large reclamation work has required construction of a new mixing plant barge for each project, but the new mixing system can be combined with existing compressed air-mixture pipeline transfer systems, further reducing total costs.

Conclusion

Japan is small and densely populated, so marine engineering and construction involves various problems which affect other construction work, fisheries, and other projects. Improvement of the marine environment by dredging soft mud is essential for Japan in the future. R&D on secondary treatment such as solidification of land reclamation will continue in the future.

The cement and soft mud mixing technique using the compressed air-mixture pipeline as described above is a prospective method for solidification of large land areas at low cost. It is usable at reclamation sites, which have previously required a new mixing barge, in combination with the compressed air-mixture pipeline transfer system of large capacity.

The new solidifier mixing system is expected to be used widely in reclamation work on a larger scale, and R&D in this area will be continued.