Columbia University in the City of New York

Department of Civil Engineering and Engineering Mechanics

Beneficial Use of Dredge Material

<u>Progress Report</u>

Prepared for Echo Environmental, Inc., New York

By K. Millrath, S. Kozlova, S. Shimanovich, and C. Meyer

February 2001

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Preface

On May 21, 1999, Echo Environmental, Inc., and Columbia University entered a "Detoxicating Noxious Waste Research and Option Agreement". Actual research activities commenced in earnest during July 1999. The following report summarizes the progress made during the first 15 months of this research project. As work is continuing, additional reports shall be submitted to Echo Environmental, Inc., to document the work conducted.

1 Introduction

In June 1999, Columbia University, in cooperation with Echo Environmental Inc., NY (Echo), has initiated a research project to search for beneficial uses of dredge material from the Port of New York and New Jersey. This problem is of major concern to the Greater New York Metropolitan region, because shipping lanes need to be dredged to keep the Port operable and economically viable. However, the dredge material contains all kinds of contaminants, from heavy metals to oils and pesticides, which make its disposal problematic for environmental reasons.

Echo Environmental, Inc., has provided a patented chemical (Echo chemical), which is capable of chemically neutralizing heavy metals and other toxins. Therefore it has the potential of effectively decontaminating the New York Harbor dredge material.

This report summarizes the progress made during the first year of the project. During this time, emphasis was placed on various treatment methods for dredge material. Especially, the effectiveness of cementitious binders partly in combination with various chemicals was subject of extensive studies. This approach appeared to be promising, because both the liquid and solid phases of the dredge material are utilized. Also, it eliminates the need to separate fine particles, which tend to attract more pollutants.

In addition, gypsum- and lime-based binders were tested for their suitability. Such treatments prepare dredge material for beneficial use providing detoxification and, to some extent, solidification, which allow easy and secure handling during further processing.

The ultimate goal of this research is to develop a technology to detoxify the dredge material for multiple beneficial uses. One possible application is the usage of the detoxified material as aggregate for concrete. The process has to assure that the contaminants cannot leach out under normal service conditions. The safety assurances have to be such that regulatory agencies can approve the process and the general public can accept it to the extent that the concrete end products are marketable. In addition, the process has to be economically viable.

2 Background

2.1 The Port of New York and New Jersey

The Port of New York and New Jersey is the premier cargo destination and hub port on the East Coast of the United States. It serves the largest regional market in the U.S., handling over 1.7 million loaded containers annually, in addition to other goods. In 1997, the Port provided around 166,000 direct and indirect jobs [1].

Figure 1: Main shipping channels of NY/NJ Harbor [2]

Obviously, harbors and waterways can fulfill their commercial task only if the shipping lanes are of sufficient depth for navigation. With a natural depth of approximately 19 feet the Harbor is far too shallow to meet present shipping requirements. Many modern oil tankers, bulk vessels, and container ships need a channel depth of at least 45 feet.

Thus, the Port's operator, the *Port Authority of New York and New Jersey* (PANY/NJ), has been facing and continues to face the task of deepening existing shipping channels in order to keep the Port competitive with other harbors. In addition, shipping lanes need to be dredged on a regular maintenance basis to prevent silting up. The governmental agency charged with supervising all dredging activities is the *US Army Corps of Engineer*s (USACE). The regulatory duties for maintaining clean water and air belong to the *US Environmental Protection Agency* (USEPA). Other regulatory agencies and pertinent legislative acts are summarized in Sect. 2.3.

2.2 Costs of Dredge Material Disposal

Prior to 1992, it was common practice to dump all dredge material in the ocean on the Continental Shelf in the New York Bight. The use of this area for disposal dates back to the mid-1800s. Since 1973 the New York Bight Dredged Material Disposal Site, also known as *Mud Dump Site* (MDS), was used for the dumping of sediments dredged from the Port of New York and New Jersey. The site was officially closed on September 1, 1997, and re-designated as the Historic Area Remediation Site (HARS) under 40 CFR Section 228 (*Code of Federal Regulations*) [3].

The stop to ocean dumping prohibits the bulk of dredge material from being placed at the HARS. The non-contaminated portion of dredge material can be considered to be HARS-suitable and thus be used for remediation of the area surrounding the MDS. Public resistance against ocean dumping in general was

widespread. Such sentiment is still being encountered when specific material has to be classified as HARS-suitable or –unsuitable, and it is expected to persist in the future. At present, about 75% of the dredge material, or 2.7 Million Cubic Yards (CY) per year, are judged to be HARS-unsuitable [2].

The cost of dredge material disposal was about $3 / CY before 1992. Due to changes in regulations and restrictions of common options the disposal costs increased steadily, reaching a maximum of $118 / CY in 1996, when the dredge material was temporarily shipped to Utah and Ohio, because the option of ocean dumping was eliminated abruptly and no immediate alternatives were available at that time.

In 1996/97, the cost of dredge material disposal fell to $56 / CY. With the introduction of the so-called Newark Bay Confined Disposal Facility, the cost decreased to $34 / CY in 1997. Additional pits are planned or under construction. Existing landfills cannot be used because of expected leaching of contaminants. The PANY/NJ considers disposal costs of $25 / CY as a target which would be economically sustainable for Port operation. Periodic *Dredge Material Managing Plans* (DMMP) are established by the USACE for future requirements. In 1996, representatives of New York and New Jersey, in cooperation with USEPA, USACE, and PANY/NJ developed a *Joint Dredging Plan for the Port of New York & New Jersey* [4].

2.3 Regulatory Agencies and Legislative Acts

The major agencies with regulatory or advisory responsibilities are as follows:

- US Army Corps of Engineers (US ACE)
- US Environmental Protection Agency (US EPA)
- National Oceanic and Atmospheric Administration (NOAA)
- US Department of Energy (US DOE)

In addition, the following local, state and federal agencies have various authorities over dredging operations granted to them by the states of New York and New Jersey:

- New Jersey Department of Environmental Protection
- Office of New Jersey Maritime Resources (ONJMR)
- New York State Department of State, Division of Coastal Resources
- New York State Department of Environmental Conservation
- Institute Of Marine and Coastal Sciences at Rutgers University
- New Jersey Institute of Technology
- Rensselaer Polytechnic Institute
- Stevens Institute of Technology
- Brookhaven National Laboratory of the U.S. Department of Energy

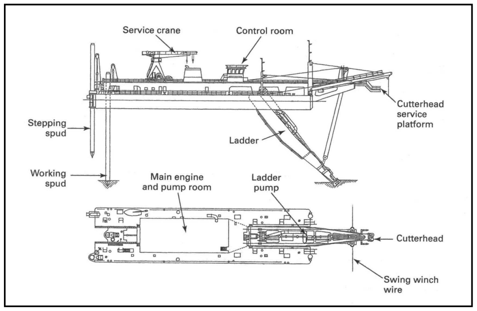
The following legislative acts have direct or indirect bearing on issues related to dredging of U.S. waterways:

- Federal Water Pollution Control Act Amendments or Clean Water Act (CWA), 1972 and 1977
- Town and Country Planning Act, 1971
- Food and Environment Protection Act (Part II), 1985
- Control of Pollution Act (Part II), 1984
- Coast Protection Act, 1949
- Coastal Zone Management Act (CZMA)
- Endangered Species Act (ESA), 1973
- Fish and Wildlife Coordination Act (FWCA), 1958
- Marine Protection, Research, and Sanctuaries Act (MPRSA), also known as Ocean Dumping Act, 1972
- Merchant Marine Act of 1920
- National Environmental Policy Act (NEPA), 1969
- Rivers and Harbors Act (RHA) of 1899, also known as The Refuse Act
- Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, also known as London Convention of 1972
- Water Resources Development Act (WRDA), 1990
- Comprehensive Environmental Response, Cleanup and, Liability Act (CERCLA), also known as SUPERFUND, 1980
- Resource Conservation and Recovery Act (RCRA), 1976
- Water Quality Act, 1987
- Clean Air Act
- NY State Department of Environmental Conservation, Division of Solid Waste: 6 NYCRR Part 360 (Solid Waste Management Facilities)

2.4 Dredging Processes

The dredging process requires a dredging unit (dredger) and a transportation or placement unit. Usually dredge material is distributed by barge or pipeline. There are basically four different types of dredgers available [5]:

(a) Cutter Suction Dredgers



Cutter suction dredgers free the material to be excavated by cutterheads and pump it through pipelines, called ladder, to the distribution unit (Fig. 2).

Figure 2: Cutter suction dredger [5]

Suction dredging can be stationary or continuous. The cutterhead is mounted on top of the pipeline and consists of a ring and a basket (Figure 3). Teeth on the basket loosen the material, which is then pumped through the opening by a vacuum pump. Strength and length of teeth and arms can be adapted to specific site conditions.

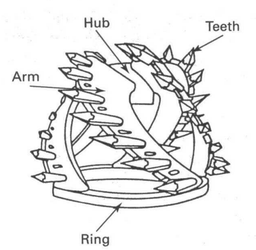
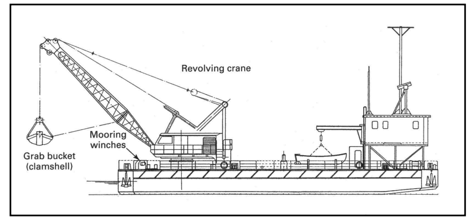


Figure 3: Cutterhead [5]

(b) Backhoe or Grab Dredgers



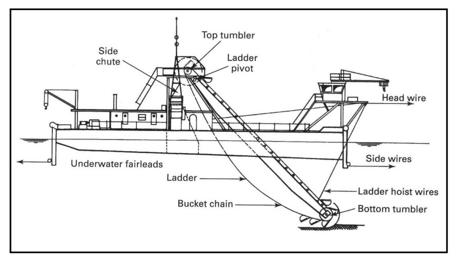
Grab dredgers (Figure 4) and backhoe dredgers (Figure 5) are excavators mounted on top of pontoons or barges.

Figure 4: Grab dredger [5]

Backhoe dredgers are most frequently used since the excavator unit consists of regular construction equipment fixed on a floating unit. Acquisition and maintenance costs are relatively low. Of the available dredging systems, the backhoe or grab dredgers are most efficient when used for small sites. The main disadvantage of backhoe and grab dredging is a discontinuous material flow.

Figure 5: Backhoe dredger [5]

(c) Bucket Dredgers



One example of a bucket dredger is the chain bucket dredger (Figure 6).

Figure 6: Chain bucket dredger [5]

Buckets fixed to a chain scratch on the surface and transport the loosened material to the distribution unit (Figure 7). The process is continuous; but due to high maintenance costs, chain bucket dredgers are no longer competitive with other dredgers.

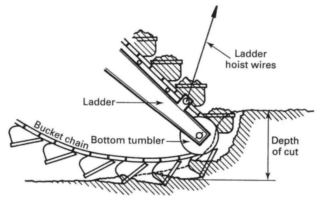


Figure 7: Cutting with bucket chain [5]

(d) Trailer Dredgers

Trailer dredgers tow nets above the submarine surface and thus fill them with material. These are not widely used due to high environmental impact (similarities with the trailer fishing process are obvious) and difficulties in setting the right parameters for successful dredging.

Also available are scrapers, which combine dredging, transport and/or distribution in one unit. Relatively low load capacities and long interruptions for transportation limit the use of scraper dredgers to small sites with short travel distances or one-day operations. For environmental protection the amount of particles spread out by dredging is often limited. Thus closed pipeline dredgers such as suction dredgers are preferred when the danger of material loss during the dredging process is high. This can occur in the presence of strong current or tidal movements. Usually the dredging process is only possible when the sea is relatively calm.

3 Dredge Material Beneficiation

Prior to 1992, it was common to dispose of dredge material in its untreated form in the open ocean. Today, such disposal is prohibited because of clean-water legislation and other environmental concerns. The various contaminants contained in such dredge material may have severe environmental impacts of chemical, physical, or biological nature, including change of nutrient balance, inhibition of growth, inhibition of respiration, and overtaxed adjustment, which widely affect the bottom fauna [6].

Three management alternatives may be considered for dredge material: open-water disposal, confined (diked) disposal, and beneficial use (Figure 8). Other treatment opportunities such as natural recovery, bioremediation, landfills and in-situ capping are available [7] but are not considered any further herein.

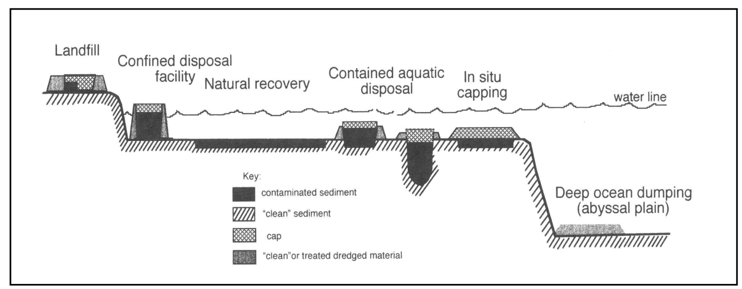


Figure 8: Concepts of dredge material disposal [3]

3.1 Open-Water Disposal

Open-water disposal refers to the placement of dredge material in rivers, lakes, estuaries, or oceans. As mentioned above, this disposal option has become unacceptable in the face of pertinent legislative action and public opposition. Also, international agreements to limit or ban open-water disposal have been entered into, and these are being modified regularly.

Recently, an evaluation method of open-water disposal has been suggested, which is based on a stress factor (material specific effects), called *Load Potential* (LP), and an ecological elasticity factor (available water reactions), called *Tolerance Potential* (TP). As long as TP is greater than LP, open-water disposal will maintain stable conditions without long-term change or damage of the environment [6]. Within the U.S., the dumping of contaminated sediments in waters other than the open ocean is not permitted under the *Marine Protection, Research, and Sanctuaries Act* (MPRSA).

3.2 Confined Disposal

Confined disposal is the placement of dredge material within diked near-shore or in upland *confined disposal facilities* (CDF). Confinement or retention structures enclose the disposal area above any adjacent water surface, isolating the dredge material completely [7]. It is the enclosed CDF area, which distinguishes this disposal method from others, such as unconfined land or *Contained Aquatic Disposal* (CAD), which is a form of subaqueous capping (Figure 8).

Confined disposal facilities have to eliminate all potential escape routes of the contaminants: effluents during placement, surface runoff, leachates, direct uptake by plants and animals and volatilization to air. Safety requires long-term monitoring and if necessary access to repair damages. Until recently, confined disposal was one way of final storage without improving the material properties. Complete isolation had to be secured indefinitely, so that the area, once dedicated for such use, will not be available subsequently for any other uses.

More recent approaches are attempting to integrate active decontamination or treatment of dredge material in confined disposal facilities. For example, the use of bioremediation techniques (see next Section) seems promising in converting a storage into a treatment facility. Dredge material is processed by repeatedly refilling the same facilities, thereby becoming readily available for further beneficial uses.

3.3 Beneficial Use

Beneficial use involves the placement or use of dredge material for some productive purpose. As disposal space becomes scarce, the need for alternatives to simple disposal increases. There are two types of beneficial use that deserve special comment. One is the *dilution* or capping of contaminated materials. The other is the substitution for other substances in either construction or building material production.

One way of capping is to *hide* abandoned, yet extremely contaminated industrial areas, so-called *brownfields*, or abandoned landfills by covering them with dredge material. Another approach is the capping of contaminated sites with stabilized and relatively clean materials. Dredge material may also be used as mine restoration cover.

Another example for beneficial use is as beach nourishment, which might be necessary if natural replacement of material moved along the shoreline by wave movement and tidal currents (littoral transport) is not available. It enhances the beach profile and protects the coastal line by preventing erosion. Beach nourishment can also aid recreational purposes, which obviously require clean material. A life span of 10 years is a common design target [8]. Usually, only the gravel and sand portion of dredge material is suitable for beach nourishment, making separation and decontamination obligatory.

Manufactured topsoil is a further possible beneficiation of dredge material (see also next Section). After mixing with cellulose from sawdust or waste paper and some type of binder (biosolids), it is processed as topsoil. Not all dredge material can be used for topsoil manufacturing. Usually only fine particles are of interest so that separation of clay and silt is required. The quality of manufactured soil products can be tested by growing tomato, marigold, ryegrass and vica. The cleanness of the dredge material decides for which specific beneficial use it can be processed. When used for agriculture purposes or production of food the material has to be absolutely clean and must not contain too many salts because these stop the growth of most plants [8].

Flowable fill is any semi-liquid blend of dredge material, residual waste material and binders. It forms a slurry, which can be poured into any desirable form and hardens rapidly. It may be used for construction but careful evaluation of quality, quantity and availability of the raw (waste) materials is mandatory and has to be conducted beforehand. Especially the quality is subjected to large variation. Flowable fills require proprietary binder and processing adapted to specific materials and site conditions [9].

Stabilization is often achieved by mixing the dredge material with fly ash, cementitious materials or lime. Untreated dredge material is a slurry, which can contain from 35% to 67% water (the amount of water relative to the weight of wet material). This material creates an unstable muddy pond when stored in an open space. Thus, solidification (Figure 9) and reduction in volume are major tasks in dredge material treatment.

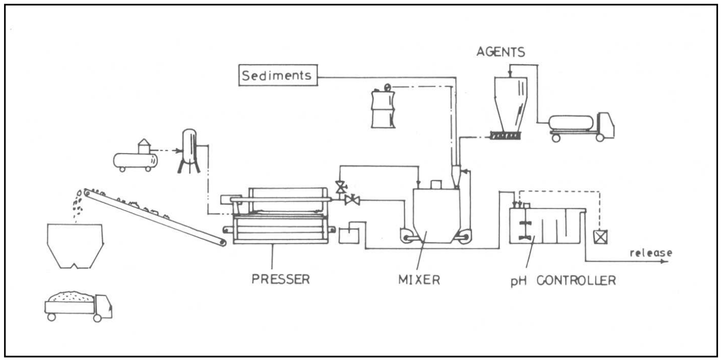


Figure 9: Solidification of dredge material (sediments) [10]

Since the contaminants tend to accumulate on the surfaces of fine particles such as clay [10], a first step in beneficial use is separation of the fines from the rest of the material. Large-scale cleaning technologies for sand-like material are available, e.g., MEchanical Treatment of Harbor Sediments (METHA) in Hamburg, Germany [11, 12] (see also section 3.5).

Also biological treatment is used for decontamination. This method was first applied in sewage treatment plants where microorganisms consume organic matter. Bioremediation techniques are based on the consumption of contaminants, especially organics such as PAHs, by microorganisms as food or energy resources. Creating a favorable environment for optimal growth of the microorganisms requires providing sufficient oxygen and nutrient content as well as controlling moisture, temperature and pH-level. The contaminant break-down by catabolism or biodegradation is generally more time-consuming than chemical and physical treatment and evaluation of the efficiency of biological decontamination may be difficult to determine [13].

Typical bioremediation technologies are windrow composting, landfarming and land treatment. For Jones Island CDF, Milwaukee, WI windrow composting has been applied. It requires placing the material in long piles and periodical mixing with mobile equipment. Thermophilic conditions (54-65°C) and correct moisture have to be maintained. Below a moisture of 40% biodegradation is slowed down considerably while above 50% moisture turning operations become difficult. Furthermore gas emissions are of concern [13, 14].

Another way to treat dredge material biologically is by phytoremediation or phytoreclamation. It combines degradation by microflora or plant-associated bacteria and enzymes (metabolism), plant extraction, i.e. removal of contaminants through plant uptake and bioconcentration, and immobilization by reducing leaching pathways. Phytoremediation can be applied in-situ and has been conducted successfully at industrial sites [15].

Dredge material placement can support habitat development. This includes the creation of wetlands, aquatic or upland habitats, and artificial islands. Over 2,000 man-made islands have been constructed in the Great Lakes, coastal and riverine areas utilizing dredge material [8].

Dredge material can be used as raw material for cement or lightweight aggregate production (rotary kiln) and the manufacture of glass tiles (plasma torch). Both processes involve high temperatures (more than 660°C) and are thus energy-intensive and costly [16]. However, high-value end products can offset these costs. Another approach is the production of so-called Eco-Blocks. These building blocks are produced with compression equipment, using mixes of lime, dredge material and sand. Decrease in contaminant concentration is achieved by blending with other materials and encapsulation [17]. Dredge material may be also used in asphalt, so far tested without promising results, or in concrete applications.

3.4 Federally Funded Projects of Beneficial Use

BioGenesis Enterprises, Inc. / Roy F. Weston, Inc. [18, 19] developed a decontamination method for dredge material based on soil washing. Organic and inorganic material is removed or separated from solid particles by treatment with high-pressured water, impact collision forces, cavitation, and oxidation. Pilot operations ran from January to March 1999 treating 700 CY of dredge material. A full-scale system demonstration project is in preparation under WRDA and New Jersey Maritime Resources (NJMR) programs. An annual production rate of 500,000 CY of sediments from NY/NJ Harbor is the goal for a planned treatment plant by 2001. The process is an integrated treatment train:

In a first step, oversized material is removed by screening the sediments. The fraction with a diameter less than 1/4 inch is analyzed before treatment. Chemical addition rates and equipment settings are adapted to the requirements. Organic pollutants are destroyed through cavitation and oxidation. Hydrocyclones and centrifuges separate liquid and solid phases. The cleaned sediment portion can be used as manufactured soil or landfill cover, but the wastewater has to be treated separately due to heavy metal contamination [19].

Metcalf & Eddy, Inc. [18, 20] combines several treatments to create a sequential decontamination system for dredge material. It uses a soil washing method called HYDRO-SEP^{SM}, a solvent extraction process to remove organic contaminants called ORG-X^{SM}, and a solidification/stabilization technology called SOLFIX^{SM}. Bench scale tests have been performed.

Westinghouse / Global Plasma Systems [18, 21, 22] use a plasma torch treatment to decontaminate dredge material. The process is based on thermal treatment that melts the material. It requires preliminary screening, dewatering and fluxing. In 1999, about 4 CY of dredge material were vitrified and an additional 2.5 CY were first vitrified and then converted into sintered architectural tiles for demonstration testing. Plans for a demonstration plant in New York or New Jersey are under development

The rate of decontamination is very high. For organic compounds this process is the most effective one, reaching destruction rates of over 99%. The method is extremely energy-intensive, which leads to gross processing costs of $85 to $112 per CY [22]. The end product can be used in architectural glass tiles of high value and thus may provide some financial compensation. It makes only sense to apply vitrification on very highly contaminated dredge material and therefore it is of questionable commercial potential.

Institute of Gas Technology (IGT) / Endesco [18, 23] apply a reactive melter (rotary kiln) with temperatures of 1200-1400°C to decontaminate dredge material and use it in structural grade cement. Similar to the Westinghouse / Global Plasma process, the so-called Cement-Lock™ Technology provides very effective decontamination in combination with high energy consumption. A demonstration plant with a production rate of 100,000 CY per year is planned.

US Army Corps of Engineers, Waterways Experiment Station (WES) [24] produced manufactured topsoil by blending cellulose waste solids (yard waste, compost, sawdust, wood chips) and biosolids (cow manure, sewage sludge) with as-dredged material. This approach unites dilution and, over time and only up to uncertain extent, bioremediation. Bench-scale and pilot-scale tests were performed leading to the following conclusions: topsoil may be a desirable application at relatively low costs, combining simplicity and easy implementation without prior dewatering. Greatest disadvantages are the unknown degree of degradation of organic compounds and the unpredictable fate of heavy metals. It was recommended that a large-scale demonstration should be conducted in conjunction with an active decontamination process [24].

MARCOR Environmental of Pennsylvania, Inc. [18, 25] uses a chemical stabilization technology known as Advanced Chemical Treatment to decontaminate dredge material. Bench scale tests have been performed on untreated sediment. After blending dredge material with lime, cement and / or fly-ash it sets in a hardened, granular soil-like condition with lower water content and improved structural or geotechnical properties [24]

Several federally funded projects are listed in Table 1, including those for which no detailed information is readily available.

Table 1: Dredge Material Decontaminanation Technologies [26]

Company	Technology	Suggested Beneficial Uses
BioGenesis Enterprises	surfactant-based soilwashing (chemical precipitation followed by UV/oxidation)	landfill cover topsoil replacement manufactured topsoil
Biosafe, Inc.	fluidized-bed steam stripping (thermal desorption at 1200ºF and thermal destruction at 2200ºF)	landfill cover construction backfill
Institute of Gas Technology	Cement-Lock™ (reactive melting using modifiers at 2500ºF)	construction-grade cement
IT Corporation	thermal-desorption (thermal treatment at 1000ºF followed by chemical stabilization)	artificial reefs
MARCOR Environmental and Kiber, Inc.	chemical stabilization (mineralization using aluminum-silica-oxide reagent)	construction backfill secondary building material
Metcalf & Eddy	solvent extraction with stabilization (separation followed by extraction, stabilization or combination of both)	landfill cover construction backfill highway sub-base aggregate
Westinghouse Science and Technology Center	Plasma-arc vitrification (destruction and immobilization in glass matrix at 5000ºF)	fiberglass glass fiber products rock wool insulation
Waterways Experiment Station	solidification / stabilization (binding by cement, fly-ash, lime)	construction backfill secondary building material artificial reefs
	manufactured soil (dilution by clean materials, fertilizers and conditioners)	landfill cover construction backfill

3.5 Dredge Material Disposal in Other Countries

Dredge material disposal poses problems for nearly all major ports in the world. Before environmental protection became a political issue, ocean or open-water disposal was the most common way to solve the problem. Nowadays harbors are in dire need to find alternatives. Some of the treatment methods used in Europe shall be described briefly.

In the Netherlands, toxicity testing is not required for the licensing of off-shore disposal as is common practice in the U.S. Rotterdam, which is the world's largest port, disposes of slightly contaminated dredge material in the North Sea at a site called *Loswal Noord*. More highly polluted material is placed in an isolated disposal site called *slufter* [27, 28]. Bioassays based on tests with oysters, amphipods, and mussels were suggested for quality assurance and establishment of sediment quality criteria [27]. Highly contaminated sediments from the Petroleum Harbor in Amsterdam are treated by biodegradation in bioreactors. The remediation chain includes separation by hydrocyclones, froth flotation of coarse particles, and biological treatment of the silt fraction [29, 30].

Hamburg, Germany, constructed a large-scale plant in 1993 for mechanical separation and dewatering of polluted sediments, called METHA. Its annual throughput rate is 1.8 million CY. Dredge material is separated and dewatered in a continuous process. End products are clean sand and a contaminated fine fraction (particle size <63µm), which has to be disposed of [11, 12].

The port of Bremen, Germany, uses the disposal site *Deponie Bremen-Seehausen* to dispose of approximately 1 million CY of dredge material annually [31]. In both German cities intense research on the use of dredge material in brick production led to the development of the *Hanseaten-Steine*. These are bricks burnt at 1000°C, using the fine, yet highly contaminated, fraction of dredge material. Up to 65% of the dry raw materials are substituted by dredge material. Manufacturer is Hanseaten-Stein Ziegelei GmbH, Hamburg. Due to low public acceptance of the end product, the University Bremen suggested to approach only public clients [31, 32].

4 Dredge Material Properties

Dredge material is naturally accumulated sediment or, in the case of channel deepening, existing rock or soil, which is excavated from the bottom of waterways. Dredging is necessary to maintain sufficient depth for safe and efficient navigation. Dredge material may be contaminated with various contaminants from different sources over various time periods. Thus it is difficult to predict its properties.

10,000 years ago the ocean level was relatively low and New York and New Jersey were on a dry coastal plane. With a rising water level extensive erosion of soil took and still takes place. Thus, most sediments consist of traditional clay and rock minerals found in regular soil. Saturated with seawater containing municipal and industrial chemicals, these sediments constitute the bulk of the contaminated dredge material [1].

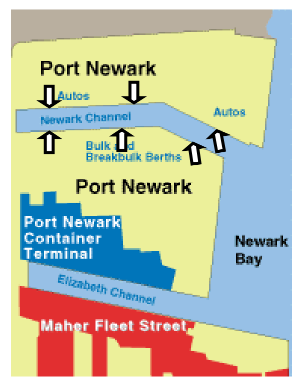


Figure 11 Port Newark [2]

Columbia University has received material from PANYNJ, which was dredged in November 1999 at six different locations in Port Newark Channel (see Fig. 11). A second batch obtained from Brookhaven National Laboratory had been dredged in 1996 at Newtown Creek. First chemical, biological, and mineralogical analyses showed surprisingly low concentrations of heavy metals, organics, and other hazardous substances.

Dredge material samples were analyzed in cooperation with Baron Consulting Company, Connecticut, and CTL Laboratory, Illinois. According to rules and regulations from US EPA the samples underwent the same treatment as aqueous or solid hazardous waste [34, 35, 36, 37]. Most of the analyses followed the *Toxicity Characteristic Leaching Procedure* (TCLP), which "is designed to determine the mobility of both organic and inorganic contaminants in liquid and solid, and multiphasic wastes" [37; page 40643]. It requires about 100 grams of material, which is subjected to an extraction process with substance specific extraction fluids, typically acids. Further details can be found in [37].

The analysis results indicate that the material consists primarily of very fine sand and silt. Oil products cover the fine particles. The average water content ranges from 55 to 60% (amount of water relative to the weight of wet material). The material contains around 9% organic compounds and small amounts of heavy metals (Table 2). The bacteriological contamination, especially with E. Coli, was sufficiently low to be of no concern.

Quartz, albite, and feldspars dominate the mineralogical composition. A typical clay mineral found is illite in a composition with mica. No montmorillonite was found, a mineral that acts like a sponge and severely retards the hydration of binders. The clay mineral content is around 15%. The aluminum oxide content is only around 13%, which indicates a high silicon proportion (similar to sand).

Table 2: Concentration of contaminants (ND - none detected)

Contaminant	Port Newark (1999)	Newtown Creek (1996)	Newark Bay Maximum values as reported in [8] (dry sediments)
Lead (Pb)	0.09 mg/L	0.17 mg/L	330 mg/L
Chromium (Cr)	ND < 0.5 mg/L	ND < 0.5 mg/L	500 mg/L
Mercury (Hg)	0.160 mg/L	ND < 0.002 mg/L	9 mg/L
Arsenic (As)	ND < 0.1 mg/L	ND < 0.1 mg/L	no information given
Manganese (Mn)	3.5 mg/L	Not tested	no information given
Cadmium (Cd)	ND < 0.1 mg/L	0.10 mg/L	no information given
Cyanide (CN)	Not tested	0.12 mg/L	no information given
PCB	100 µg/kg	ND	1500 µg/kg
Anthracene	ND	6300 µg/kg	no information given

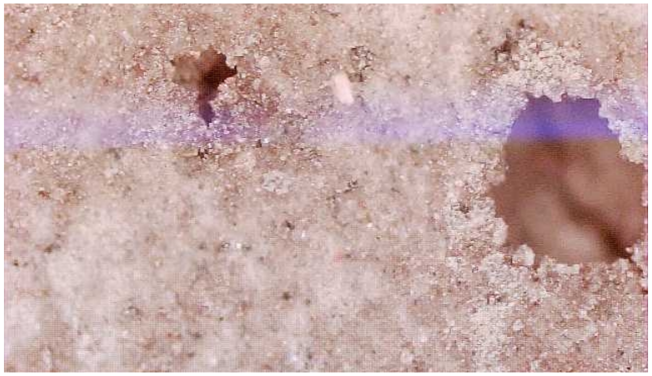


Figure 12: Optical microscope observation, 50x magnification: Dredge material from Newtown Creek dried at 110°C Note: saline crystals covering the surface

Dredge material is basically marine sediment; hence it was no surprise to find that sodium oxide is the prevalent alkali. The potassium content is similarly high. Observations by optical microscope of samples, oven dried at 105°C, 200°C, and 550°C, confirmed the results regarding mineralogical components. Saline crystals covered the surface of the samples dried at temperatures up to 210°C (Figure 12).

A typical particle size distribution as reported in [1] indicates a very high clay content of 41% and a silt content of 10%. However, the size distribution varies strongly. A standard range analyzer based on laser diffraction was used to determine size distribution and surface properties of the two specific samples. The mean diameter of dry dredge material particles from Port Newark is 11.4 μm (see also Section 5.2).

Plastic and liquid limit tests for soil identification and classification showed a sandlike behavior of the dredge material, with a plastic limit at a water content of around 77%. At that content the material loses the plastic consistence. It starts to flow and stirring is possible. This is essential for homogenizing dredge material.

Clay in the dredge material samples has specific surfaces 100 times greater than those of sand. Due to their relatively large surface-to-volume ratio and electro-chemical character, heavy metals and oil products are very likely to be adsorbed in the clay layers (Figure 13). This affects the mode of interaction between contaminants and additives. Also the surface charges of clay differ from those of regular sand.

Figure 13: Optical microscope observation, 100x magnification: Dredge material from Port Newark dried at 500°C, note: agglomerate around oil product (arrow)

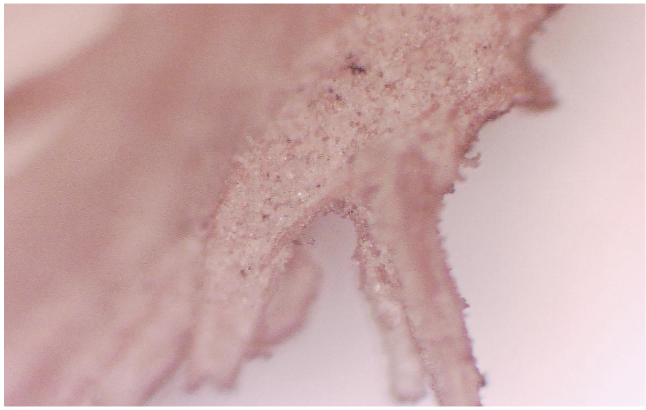


Figure 14: Optical microscope observation, 100x magnification: Piece of wood in dry dredge material covered by salts

Thus, clay acts like a sponge, i.e., it absorbs contaminants while sand offers only adsorption. Dredge material with a relatively high content of fines attracts pollutants through absorption. The concentration of heavy metals and organic compounds increases with the fineness of dredge material. Observation by optical microscope revealed that oil products cover the surfaces of small particles and large particles are covered by salts (Figure 14).

Due to the sponge action, clay absorbs water and swells. Because of surface charges between their layers some clay minerals are able to integrate charged or polarized particles or molecules, such as water, in their structure. They can form stable networks of relatively high volumes. The water is not free but physically bound to the clay layers. If untreated dredge material is used in concrete applications, subsequent cement hydration is affected not only by the various irregular substances but also by this capability to bind water. As a consequence, the water-cement ratio is affected to the point that the amount of water usable for cement hydration is not known (see also Section 6.1).

If no sufficiently high concentrations of pollutants are found in available untreated dredge material samples, it may be necessary to dope such samples in order to simulate a worst-case scenario. Such artificial contamination can either include a large number of different substances or focus on just one contaminant. Important factors to consider are the specific conditions of the dredge material in its original state such as place, age, concentrations of the various chemicals and their interaction.

During storage under water, dredge material can undergo various alteration or modification processes. These weathering effects depend on the combination of the original substances available, rate of reaction and interaction, pressure, temperature, concentrations of contaminants, and they vary greatly with time. Every change in any one of its surrounding conditions may cause an alteration of the material creating a new equilibrium. Specific components of the material are more or less sensitive to such changes, and therefore the end result can be moderately or drastically altered material.

In the current research cadmium and lead were added to dredge material so far in order to gain a general understanding of how the detoxification process works. Both of these contaminants are relatively resistant against weathering or wearing effects and are available for safe laboratory use in form of harmless nitrate salts. For artificial contamination, dredge material was dried at room temperature and then enriched by thoroughly mixing it with cadmium and lead nitrate solutions and additional water. This is considered to be just an example to demonstrate the effectiveness of experimental treatment methods. The test results are presented in Section 6.3.

5 Dredge Material Detoxification

Detoxification refers to the treatment of contaminated material in order to lower the concentration of the pollutants below acceptable limits, meeting standard requirements for either disposing of the material or for further use as a raw material. Total clean-up, i.e. the complete removal of all contaminants, is often not practical or justified, because the costs grow disproportionately as the pollutants are increasingly hard to detect.

As mentioned earlier, there are several alternatives to detoxify dredge material. Chemical treatment includes remedy with surfactants, detoxification agents, solidifying and stabilizing binders. Some physical methods are washing, separation, and thermal treatment with temperatures as high as 1500°C, which are above the melting point of dredge material (vitrification). Biological treatment, i.e. decontamination with micro-bacteria, plants or other organisms, usually is the most time-consuming process. The various methods can be combined and optimized for different site conditions or levels of contamination.

Treatment with chemical agents is relatively fast, reliable and usually more effective than biological or physical treatment. Some binders may have the capability of detoxification, encapsulation of pollutants and solidification. This chapter focuses on the initial treatment of natural dredge material with CUT powder, Echo chemical and gypsum. Other chemicals available for preliminary treatment or decontamination have not yet been subjected to detailed studies, but research will continue and the results be presented later.

5.1 CUT Powder Treatment

During our research we found a powder to serve as mineral binder, which is able to solidify dredge material and stabilize its properties. Referred to subsequently as CUT powder (short for Columbia University Treatment), both its composition and the sequence of mixing or treatment are important.

For decontamination, dredge material and CUT powder are mixed. The hydration of CUT powder causes temperatures of around 210°F and greatly reduces the water content and therefore the volume of the raw material. CUT powder solidifies dredge material. After cooling to room temperature it is readily available for further processing either dried or non-dried. Dried material might have to be ground or broken down to smaller sized particles before distribution for beneficial uses.

The structure and texture of dredge material change with CUT treatment. While the untreated material partly consists of agglomerates with similar particle size distribution as regular, but fine sand aggregate, after the CUT treatment it exhibits a very fine, widespread structure nearly without conglomeration. The particles are separated from each other, and if they are bound by hydrated CUT powder these bonds can be broken relatively easily (Figures 15 through 17).

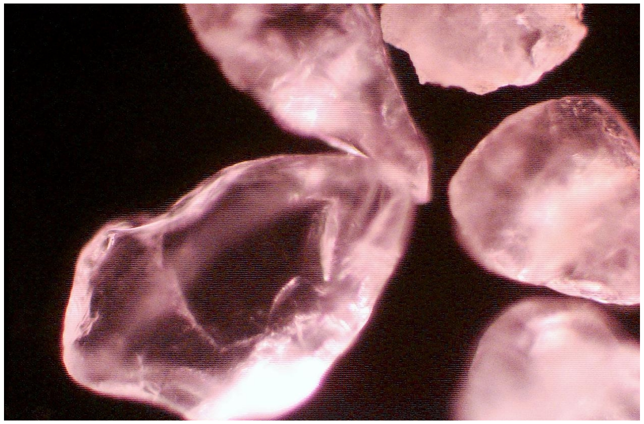


Figure 15: Light microscope observation, 100x magnification:
Regular sand aggregate, passing ASTM sieve #50 (300µm)

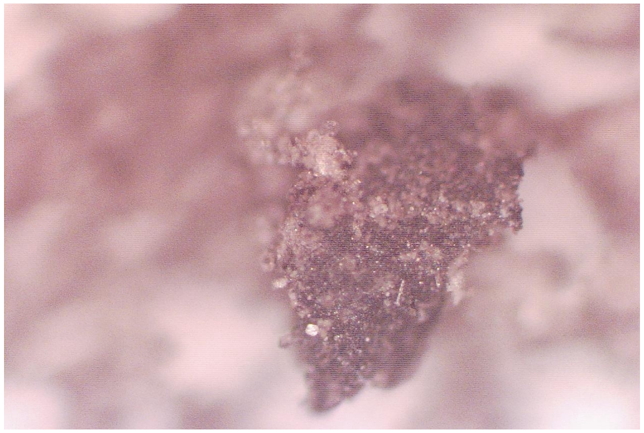


Figure 16: Light microscope observation, 100x magnification:
Dry dredge material from Newtown Creek

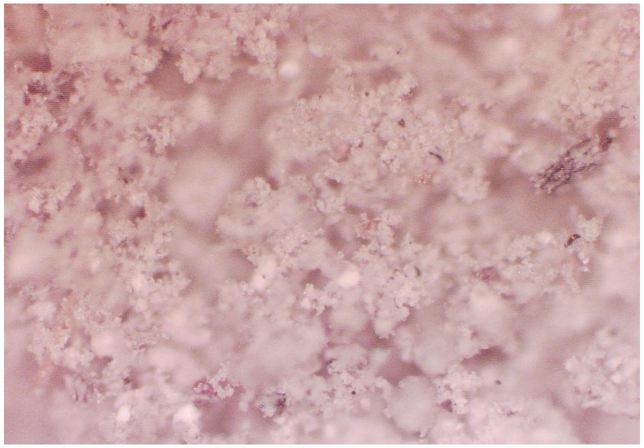


Figure 17: Light microscope observation, 100x magnification:
Dredge material from Newtown Creek after CUT Treatment,
passing ASTM sieve #50 (300µm)

CUT treatment also changes the surface properties of dredge material. The surface charge is altered, making the surface accessible to polar or charged substances such as water or superplasticizers. The treatment with CUT powder causes the formation of granular particles, whose usefulness is under study. As side benefits, increased homogeneity and less saline material on the surface were observed. The odor diminished, thus we can assume that volatile organics are either destroyed or bound.

5.2 Echo Chemical Treatment

The Echo chemical was developed to bind heavy metals. The chemical reactions create complex molecules that encapsulate heavy metals and some organic substances. In general, such agents utilize chelating ligands based on metal cations with different valences such as zinc or nickel. Because of their specific nature chelating ligands grasp certain substances and bind them chemically by forming complexes. Depending on surface charges, surrounding conditions and available reactants durable macromolecules are formed.

Treatment with the Echo chemical alone does not seem to be a sufficient preparation of dredge material for further use because it was developed for decontamination only. For that reason, it is a useful tool in detoxifying dredge material. Combining it with other treatments is recommended in order to utilize the full potential of the Echo chemical. Solidification and stabilization can be optimized in the presence of a binder such as cement. The high pH-level of cement mixes during hydration creates the base for very effective detoxification. When combined with other methods the Echo chemical treatment can be most efficient (see next Section).

5.3 Combined Treatment

It is the objective of any treatment that the dredge material becomes suitable for beneficial usage. It may not be sufficient to treat it with one single detoxification agent alone. To increase activity and effectiveness various methods should be combined. Treating dredge material separately with only the Echo chemical or CUT powder or with the combination of the two can adapt or optimize the properties of the new raw material for certain conditions.

It was one of the objectives of our research to evaluate the efficiency of various treatment methods either separately or in combination, following various sequences of mixing. It has to be shown that such treatment influences the (micro-) structure and general behavior of treated dredge material. The work reported herein focuses on the combination of Echo chemical and CUT powder only.

Surface properties and size distribution of treated material were determined by a standard range laser diffraction analyzer. The various treatment methods caused noticeable changes in the particle size distribution. Combining the Echo chemical (J) and CUT (C) powder treatments causes a shift to finer particle sizes (Figures 18 and 19). This modification tends to indicate that the surface structure is altered and conglomerates, especially around oil products, are either destroyed or spread out.

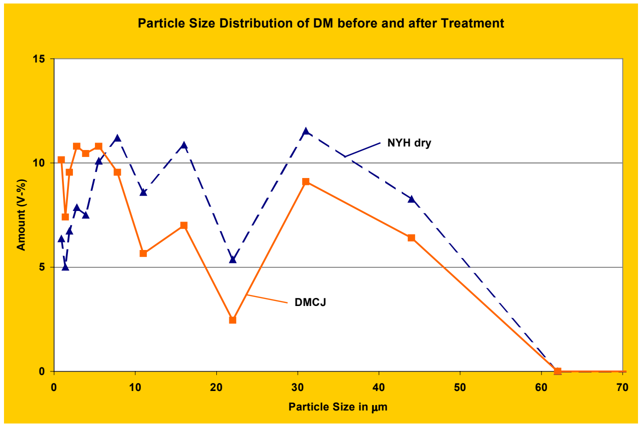


Figure 18: Particle size distribution of natural dry dredge material (NYH dry) and of dredge material after combined treatment (DMCJ)

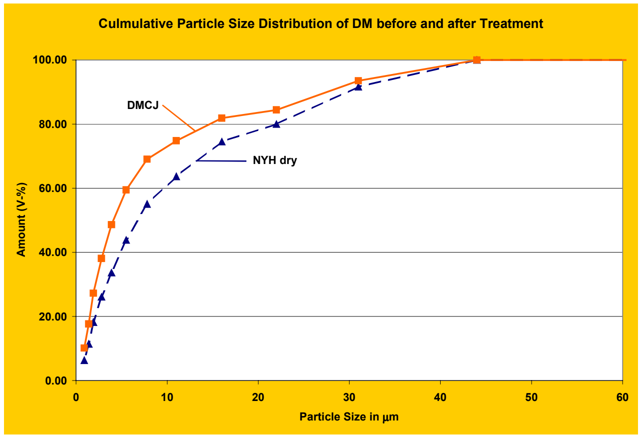


Figure 19: Cumulative particle size distribution of natural dry dredge material (NYH dry) and of dredge material after combined treatment (DMCJ)

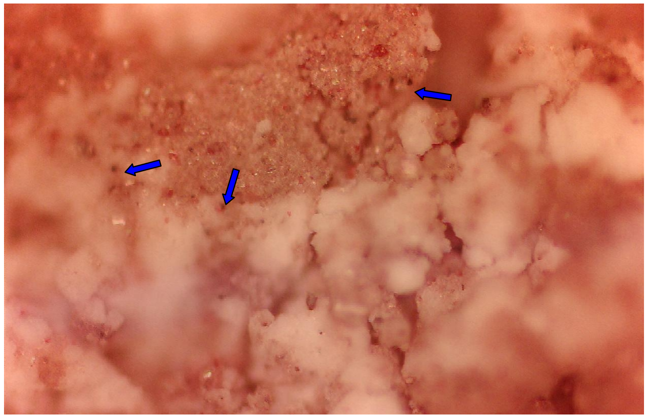


Figure 20: Optical microscope observation, 100x magnification: Dry dredge material after combined treatment (DMCJ). Arrows mark agglomerates around oil products

In Figure 20 small black dots represent agglomerates of oil products around clay particles (blue arrows). These are very small in comparison with untreated dredge material (Figure 16), which demonstrates the effectiveness of the combined treatment. Figure 21 visualizes the outspread structure of treated dredge material after ultrasonic separation. The bulk of particles is finer than untreated dredge material particles, as confirmed by the size analysis (Figures 18 and 19).

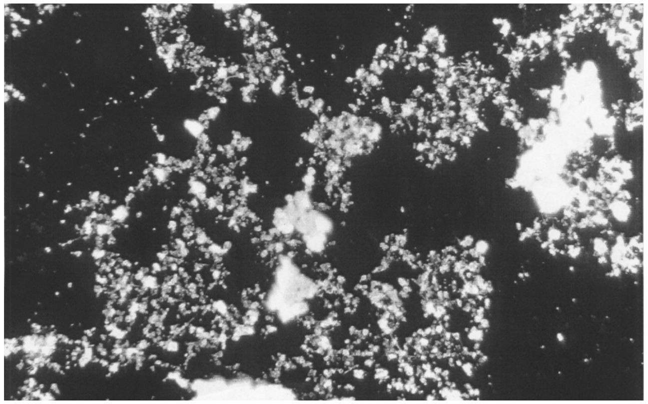


Figure 21: Optical microscope observation, 200x magnification: Dredge material from Port Newark treated with CUT powder and Echo Chemical after ultrasonic separation

To study the effectiveness of the combined treatment, dredge material samples were sent for chemical analysis to Baron Consulting Company, Connecticut, using the methods described in References [24] through [37]. One reference sample without further treatment (natural dredge material), two samples treated with the Echo chemical (J1 and J2), and one sample with combined treatment (CJ) were prepared. In the combined treatment, the CUT powder was administered before the Echo chemical. The water content was around 50% and the ratio dredge material to agent was 10:1. The leaching test results are summarized in Table 3.

Table 3: Results of chemical analysis (in ppm/dry material)

Substance	Natural DM	DM J1	DM J2	DM CJ
Leachable Cyanide	0.27	ND < 0.1	ND < 0.1	ND < 0.1
Cadmium	0.22	0.20	0.20	ND < 0.02
Lead	0.38	0.53	0.58	0.17

ND - not detectable

The data exhibit the effectiveness of the combined treatment. The treatment with only Echo chemical had little effect on reducing the amount of heavy metals detectable in a leaching test. On the contrary, a larger fraction of the contaminants present in the dredge material leached out than in the untreated samples. A possible explanation is the aforementioned destruction of micro-agglomerates and thus the advanced accessibility to reaction of the surface structure.

5.4 Treatment with Gypsum

Gypsum and anhydrite, both sulfate-based materials, are non-hydraulic binders, capable of solidifying dredge material accompanied by a dewatering process. Detoxification to a certain extent is an expected and welcome side effect. Gypsum hardens in dry condition but is soluble when in contact with water. For that reason it is usually not used for dredge material solidification or only under certain circumstances.

For concrete applications the addition of sulfates to the mix is at best questionable because it increases the risk of creating monosulfate layers or secondary ettringite formation, both of which can lead to severe damage in concrete. Hence, gypsum was not used here for preliminary treatment of dredge material before administering it to concrete mixes but only as substitute of cement for mortar preparation with artificially contaminated dredge material (see Section 4). The results are summarized in Section 6.3. The main goal was to compare the effectiveness of the two binders, especially with respect to decontamination.

6 Dredge Material as Constituent of Concrete

The characteristics of dredge material vary widely with time and source. As a consequence, it is difficult to predict in general its usefulness as a constituent for concrete. In this chapter, a number of tests will be described, that were conducted to investigate various treatment methods and to evaluate these in terms of their effects on the concrete performance characteristics. These are not only the mechanical properties of the end product but also the workability and chemical characteristics as determined by leaching tests.

6.1 Properties of Concrete with Untreated Dredge Material

Dredge material contains organics, various salts, heavy metals and other substances, which more or less affect cement hydration and may cause chemical reactions with other concrete components. Due to its fineness, it changes also the aggregate grading in an undesirable way. Delayed setting time, poor workability and performance under load may be the consequences. In spite of these problems it is necessary to study the behavior of plain concrete when mixed with untreated dredge material in order to obtain reference or baseline data, which can be used to assess the effectiveness of the various treatment procedures.

6.1.1 Preparation and Testing

The subjects of testing were both fresh and hardened concrete. The main property of fresh concrete or mortar is workability, which characterizes the ability to flow, consolidation under compaction, and segregation. Workability was measured using a flow test, for which a metal ring is filled with fresh concrete on a shock table, and after lifting the ring the mix is subjected to 25 drops of the table. The final diameter of the mix cake serves as an indicator of workability.

The main property of hardened concrete is compressive strength. This was determined using small cylinders (1" diameter, 1" height) containing 0, 5, 10, 15, and 20% dredge material as a substitute for fine aggregate (ASTM standard sieve -#50 and partly -#30, Table 4). Three specimens for each sample were tested at ages 7 and 28 days. The samples were unmolded after 24 hours and stored in a moisture room for the first seven days. The test results are shown in Table 5.

The use of one-inch cylinders was a compromise between test accuracy and the need for large amounts of dredge material. The end surfaces of the small cylinders are not perfectly plane, which affects the strength test results. But they require far less material than larger test specimens. It was felt that the tests would still yield valid results for comparative purposes, as long as all other factors were the same for all samples. Some test data of low confidence (because they defy expected trends) are marked in Table 5 with asterisks. The aggregate-cement ratio was constant, while the water-cement ratio varied with the amount of dredge material or admixtures.

The next step was to conduct leaching tests of those mixes considered to be promising. The samples were sent to Baron Consulting Company, Connecticut for analysis. Finally, tests were conducted to determine the durability and alkali-silica reactivity of selected mixes.

Table 4: Aggregate composition

Name	Reference	DM 5	DM 10	DM 15	DM 20
Aggregate/ cement ratio	2.25	2.25	2.25	2.25	2.25
Aggregate					
DM (dry)	-	5%	10%	15%	20%
Sand #8	10%	10%	10%	10%	10%
Sand #16	25%	25%	25%	25%	25%
Sand #30	25%	25%	25%	25%	25%
Sand #50	25%	25%	25%	25%	20%
Sand #100	15%	10%	5%	-	-

The grading of the coarse aggregate particles was held constant. Since dredge material is not very homogeneous, the grading of the fines varied. However, this variability was considered insignificant.

The samples were grouped into three series (Table 5). In Series A the water-cement ratio was held constant at w/c = 0.70. In Series B w/c was varied to result in an approximately constant flow of 47±2 mm. In the third series (C) the flow (47±2mm) was also held constant but with the help of a superplasticizer. To obtain reference values for consistent comparison, Series B was repeated with the same w/c but without dredge material (Series B_{REG}).

The goal of test Series A, B, and C was to correlate mechanical properties with dredge material content. The purpose of testing the samples of Series B_{REG} was to determine the influence of contaminants and salts contained in the dredge material on strength if any such exists.

Series C was used to determine the effect of superplasticizers. Prior tests showed that mixes containing dredge material could not be liquefied with lignosulfonate, a commonly used superplasticizer. This conclusion was reached by increasing the amount of 1) lignosulfonate only, 2) water only, 3) lignosulfonate solution. Flow tests were performed next with the Echo superplasticizer and STP 110. First the superplasticizer content was varied while the other concrete mix parameters were held constant. Then the flow was determined for different water-cement ratios. The results indicated that:

- the Echo superplasticizer content necessary to achieve a flow of 47 mm is ~5% for a concrete containing 20% dredge material and a water-cement ratio of ~0.6 (Figures 22 and 23);
- STP 110 is not a strong enough superplasticizer to sufficiently liquefy dredge material concrete (Figure 24).

Thus, the Echo superplasticizer appears to be the only suitable superplasticizer of the three alternatives tested. Therefore, in Series C we used 5% Echo superplasticizer with respect to the amount of dredge material.

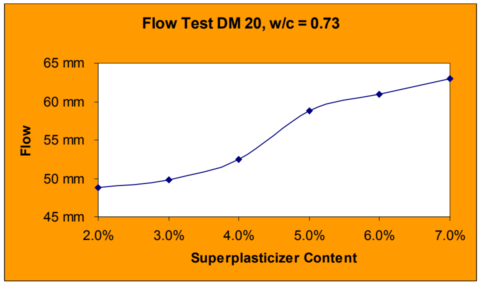


Figure 22: Flow versus supe-rplasticizer content (Echo superplasticizer)

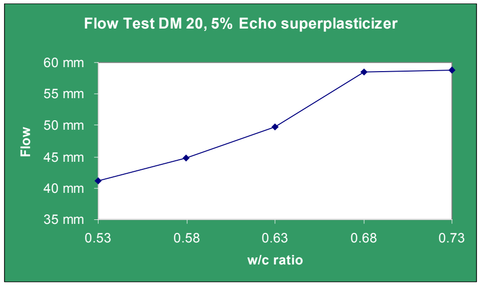


Figure 23: Flow versus water cement ratio (Echo superplasticizer)

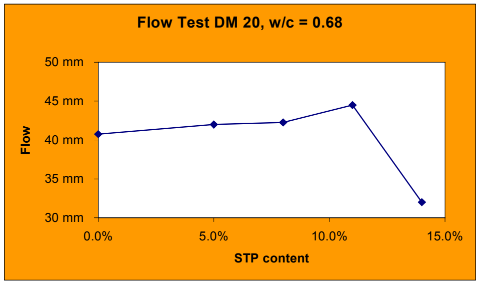


Figure 24: Flow versus superplasticizer content (STP 110)

6.1.2 Test Results

Flowability and compressive strength test results are summarized in Table 5. Detailed information can be found in Appendix 1. All strength test results are the averages for three identical specimens. The coefficients of variation for some of the samples were as high as 22%, but these could usually be explained with obvious defects or uneven specimen surfaces. For the purposes of this study, the accuracy of the tests was considered sufficient.

Table 5: Test Results for Series A, B, B_{REG}, and C

Series	DM content	w/c ratio	Super-plasticizer M-% of DM	Flow mm	7d compr. Strength MPa	28d compr. Strength MPa
A	0	0.70	0	72	21.1	33.0
	5	0.70	0	63	24.2	32.0
	10	0.70	0	49	21.0	29.4
	15	0.70	0	39	21.7	35.0
	20	0.70	0	32	19.7	30.6
B	0	0.45	0	48	53.6	60.1
	5	0.52	0	46	38.8	46.9
	10	0.64	0	47	24.1	30.8 *
	15	0.75	0	46	21.8	36.6
	20	0.88	0	46	17.9	29.8
B_{REG}	0	0.52	0	59	48.1	51.6
	0	0.64	0	70	30.8	41.3
	0	0.75	0	74	21.2	30.2
	0	0.88	0	75	15.2	19.6
C	0	0.42	0	48	48.5	52.9
	5	0.45	5	48	49.2 *	43.7 *
	10	0.50	5	47	33.2	37.1
	15	0.57	5	46	27.4	30.1
	20	0.63	5	46	25.9	39.9 *

* Test data of low confidence

The results in Table 5 permit the following observations:

1. As the dredge material content increases from 0 to 20 %, the flow gets reduced by more than factor 2, if the w/c is constant, i.e., the workability drops drastically (Series A, Figure 25). The strength, however, is barely affected (Series A, Figure 26).
2. To maintain a constant flow of about 47mm, the w/c-ratio has to be increased with increasing dredge material content. As a result, a considerable drop in strength is being experienced (Series B and C, Figures 26 and 27).
3. Increasing the w/c-ratio without adding dredge material (Series B_{REG}) causes an increase in flow and reduction in strength, as one would expect. Comparing corresponding samples of Series B and B_{REG}, we notice that small percentages of dredge material lead to lower strength, but this is not the case for samples containing larger amounts of dredge material. The flow in Series B_{REG} increased rapidly with amount of water added.
4. By adding a superplasticizer, the same flow of 47mm can be achieved with lower w/c-ratio, therefore the strength is expected to be higher. Some test results defy this trend because of the small specimen size, as mentioned earlier.

In conclusion, concrete made with up to 20% dredge material seems to behave like regular concrete in that it exhibits a strong inverse relationship between strength and w/c-ratio. The decrease in workability places an upper limit on the amount of dredge material that may be added. The test results obtained so far do not permit any conclusions about the effect of contaminants and salts on strength. If there is such effect, the small size of specimens and the resulting large statistical scatter of test results make it too difficult to detect it.

However, it was observed that dredge material affects the rate of hydration. Samples containing 20% dredge material could be unmolded only two days after casting unlike the other specimens, which were usually unmolded after 24 hours.

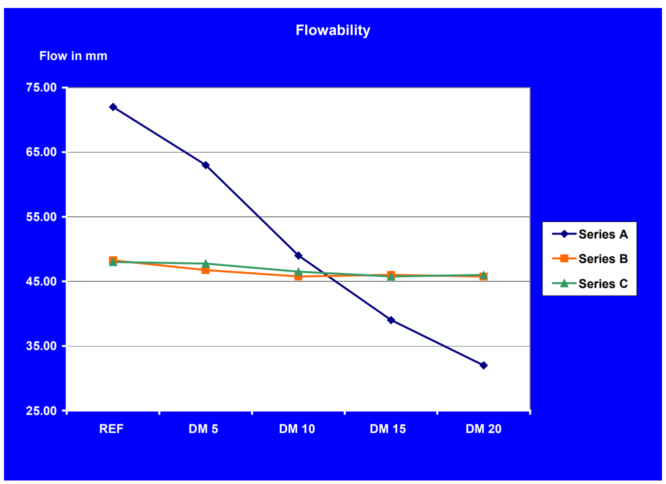


Figure 25: Workability (flow) vs. DM content

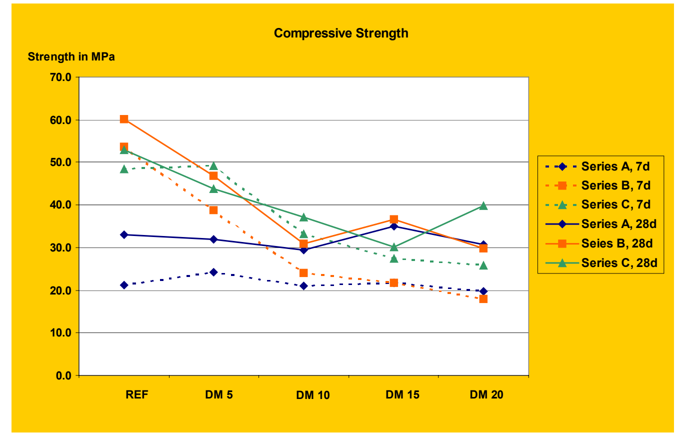


Figure 26: Compressive strength vs. DM content after 7 and 28 days

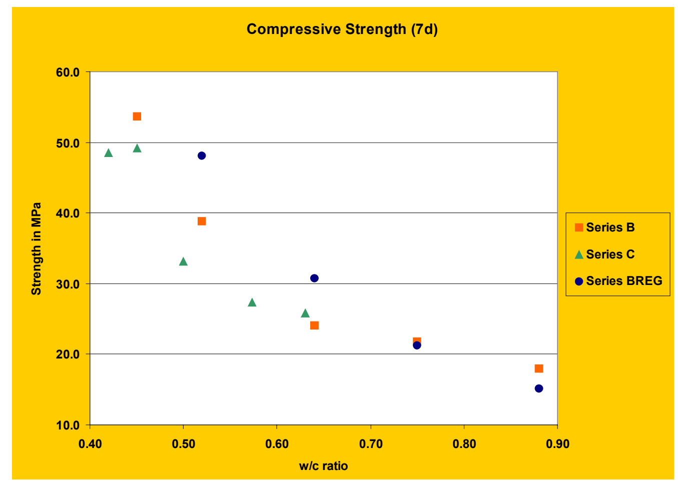


Figure 27: Seven days compressive strength vs. w/c ratio

In sum, the results obtained so far indicate that using dredge material in concrete may be feasible. Dredge material has sand-like properties and thus is suitable as a substitute for regular aggregate, without greatly affecting the strength. As in regular concrete, strength decreases rapidly with increasing water-cement ratio (Figure 26). An optimum dredge material content has not been found yet, but it has been shown that the decrease in workability places an upper limit on the percentage of dredge material.

6.2 Properties of Concrete with Treated Dredge Material

Dredge material may be mixed with gypsum, anhydrite, CUT powder, or other chemicals in order to solidify it. In that state it might be added to concrete as an admixture or a substitute for regular aggregate. The primary focus was on treating dredge material with CUT powder and the Echo chemical. We specifically excluded treatment with sulfate-based materials because of their potential to increase alkali-silica reaction in the concrete.

6.2.1 CUT Powder Treatment

The CUT treatment for concrete includes two steps. First, dredge material and CUT powder are mixed. The hydration of CUT powder reduces the water content drastically and is accompanied by generation of heat. After cooling down to room temperature, the material is mixed with the other concrete constituents in a second step. Since the powder is expected to contribute to subsequent hydration and also strongly influence the mechanical properties such as compressive

strength, it is considered to be part of the binder and was substituted for an equal amount (by weight) of cement.

CUT powder treatment poses some difficulties in handling the dredge material. The workability of the mix for 1"x1" mortar cylinders is so poor that standard production methods result in a very porous material with substandard properties. Samples with CUT powder treatment exposed no effluents while saline debris covered the bottom surface of the samples containing dredge material without prior CUT powder treatment (Figure 28).

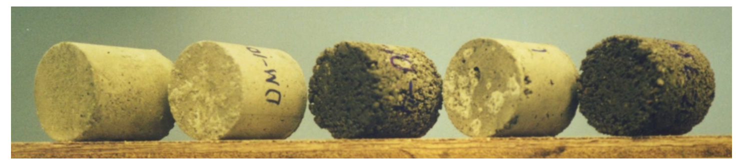


Figure 28: Samples: REF, 10% DM, 10% DM+CUT, 20% DM, 20% DM+CUT (from left to right)

6.2.2 Echo Chemical Treatment

One objective of the work reported herein was to evaluate the effectiveness of the Echo chemical as measured by leaching tests of concrete specimens containing treated dredge material. The water content of the agent is about 83%. This water has to be accounted for in the calculation of the w/c-ratio. Often chemical agents like the Echo chemical perform extremely well in alkali conditions, which can be found, e.g., in concrete pore solutions. The efficiency may increase with concentration of contaminants and site conditions.

6.2.3 Combined Treatment

Prior treatment should prepare dredge material before complementing or replacing regular aggregate. The properties of concrete containing dredge material treated with both the Echo chemical and the CUT powder vary with the mixing sequence and time.

6.2.4 Test Plan and Test Results

The experiments included treatment with CUT powder (C) or the Echo chemical (J) or both (Table 6). One goal was to determine if the mixing sequence has an influence on strength. Hence, Table 6 indicates the order, in which the CUT powder and/or Echo chemical were administered.

The mixing equipment had to be modified to fulfill the special needs of handling dredge material. Concrete mixes containing such material tend to be very sticky so that a regular mixer was not suitable for sufficient homogenization. We designed a new mixing paddle for a drilling machine. For samples 1 through 18 in Table 6 regular equipment was used, whereas samples 19 to 24 were mixed according to a new procedure using the drilling machine.

The tests compared two different approaches. In the first approach, both treatment methods were applied directly while mixing the concrete, allowing the mix to cool down after the exothermic reaction had taken place. In the other approach, dredge material was treated first, then dried at room conditions for two weeks and finally used in the concrete batch as pulverizable aggregate. Samples produced by the latter procedure are identified in Table 6 by indicating a drying period.

The dredge material was generally used as substitute for fine aggregate. In the samples with partial cement replacement by CUT powder, both components act as binders. Thus, the water-to-binder ratio (w/bind) is used instead of the usual w/c. The water content available in dredge material for the hydration of cement or CUT powder is estimated to be 55%. With an aggregate-to-binder-ratio of 2.25 and a fraction of 0.45 for the amount of solids within dredge material, the w/bind-ratio of samples containing 20% dredge material results in a relatively high value of 0.55 (dredge material-to-cement ratio: 0.20x2.25/0.45 = 1.0; thus, with water content of 55%: w/bind = 0.55)

At that w/bind-ratio the workability of concrete mixes containing 20% DM was so poor that it had to be increased to 0.70 or higher. Still, the flow was less than the targeted 47±2mm. Since the first set of experiments did not use superplasticizers, it should be possible to achieve a suitable flow using the Echo superplasticizer, the effectiveness of which was already shown (see Section 6.1.1). All test results are summarized in Table 6 (below). Appendix 2 has further details.

Table 6: Test Plan and Test Results

Sample No.	DM Content *M-% of aggr.*	1st Treatm.	2nd Treatm.	Drying Period	w/bind-ratio	Flow 1) *mm*	28d Density *g/cm³*	7d Strength *MPa*	28d Strength *MPa*
1	0	-	-	-	0.47	46	2.21	25.5	40.7
2	10	-	-	-	0.48	20	2.27	41.7	53.7
3	20	-	-	-	0.55	20	2.13	16.6	23.9
4	10	CUT	-	-	0.48	none	1.91	6.8	13.2
5	20	CUT	-	-	0.57	none	1.74	2.2	5.5
6	10	Echo	-	-	0.48	36	2.14	29.8	32.4

Table 6: Test Plan and Test Results (continued)

Sample No.	DM Content M-% of aggr.	1st Treatm.	2nd Treatm.	Drying Period	w/bind-ratio	Flow 1) mm	28d Density g/cm³	7d Strength MPa	28d Strength MPa
7	20	Echo	-	-	0.55	23	1.98	26.6	31.6
8	0	Echo	-	-	0.47	51	2.20	26.0	28.3
9	20	CUT	Echo	-	0.55	none	1.87	13.1	20.1
10	20	Echo	CUT	-	0.55	none	1.89	11.7	20.4
11	0	-	-	-	0.71	NP	2.05	26.5	26.9
12	20	Echo	CUT	-	0.87	NP	1.89	25.1	23.9
13	20	CUT	Echo 2)	-	0.89	NP	1.87	19.4	22.1
14	20	Echo	-	-	0.70	NP	1.94	27.4	30.1
15	20	CUT	Echo	-	0.84	NP	1.88	23.9	22.5
16	20	CUT		Yes	0.70	37	1.84	16.7	17.6
17	20	CUT	Echo	Yes	0.70	none	1.97	18.8	18.9
18	20	Echo	CUT	Yes	0.70	30	1.92	15.9	18.5
19 3)	20	CUT	Echo 4)	Yes	0.70	37	1.90	17.5	17.4
20 3)	20	CUT	Echo	Yes	0.70	none	1.93	14.9	13.1
21 3)	20	CUT	Echo	Yes	0.70	NP	1.93	20.9	26.4
22 3)	20	CUT	Echo 4)	Yes	0.70	NP	1.89	21.9	22.5
23 3)	20	-	-	-	0.70	NP	2.00	18.5	26.2
24 3)	20	Echo		-	0.70	NP	1.94	16.7	30.4

1) NP No test performed.

2) Echo chemical was previously mixed with cement before administering to mortar.

3) Modified equipment was used.

4) Echo chemical was administered to the mix after drying period.

The results in Table 6 permit the following observations:

1. The reference mix that contained no dredge material produced the highest-strength concrete. Whether treated or not, the addition of dredge material almost always reduces strength and always

flowability. This result confirms the basic fact that dredge material per se is not a good constituent for concrete, regardless of its various contaminants. Any effort to incorporate this material in concrete for waste disposal purposes therefore has to minimize the detrimental effect on the concrete. However, the use of 10% dredge material in sample 2 yielded in an exceptionally high compressive strength. It is assumed that this is caused by the non-constant workability or compactability and by the variation of tests with small cylinders (see Section 6.1.1).

2. For samples with w/bind-ratios of 0.55 or less, a drastic drop in compressive strength accompanied the CUT treatment (compare samples 2 and 4 or 3 and 5). As mentioned in section 6.2.1, those specimens tended to be very porous because of the poor workability of the mixes.

3. When treated with the Echo chemical, strength decreased for zero DM content (compare samples 1 and 8) and for 10% DM content (compare samples 2 and 6). However, for 20% DM content (samples 3 and 7), a strength increase was registered. If administered together with the CUT treatment, the Echo chemical moderated the strength loss (compare samples 9 and 10 with 5 and Figure 29).

4. In all cases, strength strongly correlated with density (see Figure 30). Also, strength tends to increase slightly with higher flow, because the better flowability indicates less porosity.
5. A w/bind-ratio of 0.70 proved to be suitable for comparative purposes. It was a compromise between adequate workability (which was more difficult to achieve at lower w/bind-ratios) and acceptable strength loss. For example, comparing samples 7 and 14, it can be seen that a negligible strength loss accompanied the large increase in w/bind-ratio from 0.55 to 0.70. Comparing samples 9 and 15, it is noted that the increase in w/bind-ratio from 0.55 to 0.84 leads even to a small strength increase. The density of samples with w/bind = 0.70 was almost constant at about 1.90 g/cm^3.
6. It appears that the order, in which the CUT and Echo chemical were administered, had little influence on compressive strength (e.g., compare samples 9 with 10, 12 with 15, and 17 with 18). Still, the Echo chemical consistently increased the strength (compare samples 16 and 22, 23 and 24, 18 and 16).
7. The prior mixing of cement and Echo chemical did not strongly affect the mortar properties and thus is considered unnecessary (samples 13 and 15).
8. The two-step procedure, in which the material is permitted to dry during a two-week period, made the material much easier to work with in the laboratory than the one-step procedure. The strength

test results showed a slight decrease for specimens prepared by the two-step technology, but those samples seemed to be more homogenous.

9. The modified mixing procedure used for samples 19 through 24 (Table 6) improved the mixing of concrete containing DM. Not only did the samples look far more homogenous and were less porous, also the compressive strength for the same mix compositions increased when the new equipment was used (samples 21 and 22), compared to mortar samples prepared with regular technologies (samples 19 and 17).

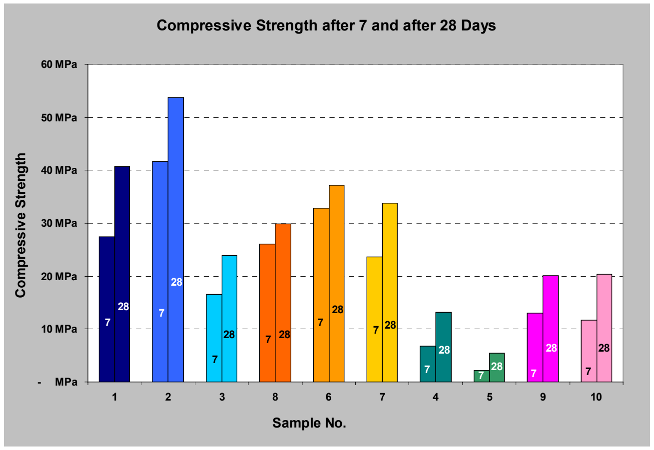


Figure 29: Compressive Strength of 1"x1"-mortar cylinders with the various treatments after 7 and 28 days

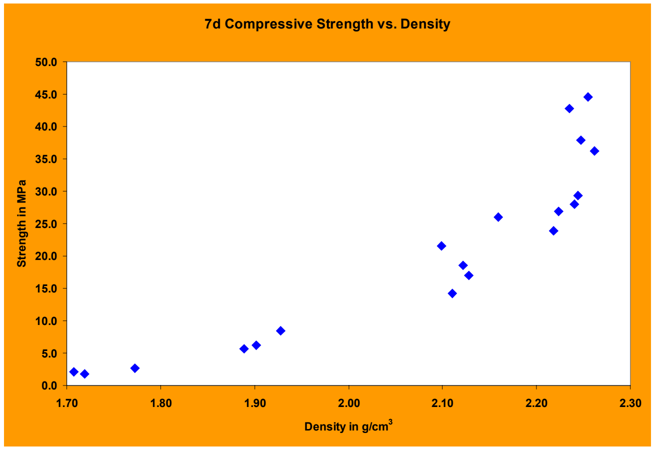


Figure 30: 7 Days Compressive Strength versus Density

Baron Consulting Company, Connecticut conducted leaching tests on mortar samples produced with the same material as samples 21 through 24 of Table 6, each containing 20% dredge material. Sample 23 contained dredge material without any treatment, sample 24 was treated with the Echo chemical, and samples 21 and 22 were treated with two variations of the combined procedure. For sample 21, the dredge material underwent CUT treatment before the Echo chemical was added. For sample 22, dredge material was subjected to CUT treatment, and then, after the drying period, the Echo chemical was administered during mortar preparation.

The samples were tested for compressive strength before being sent to Baron Consulting. Hence, the age of the samples at the time of the leaching test was about 5 weeks. The source of the DM was the same as for the specimens, for which leaching test results were reported in Table 3. Thus, we could assume the level of contamination as known. However, the leaching procedures in both cases, wet and hardened material, are not the same so that the results differ.

The results of the leaching tests are summarized in Table 7 and clearly show the effectiveness of both treatment methods when applied to mortar samples. The Echo chemical alone reduced the leachable cyanide concentration by about 35%, whereas in combination with CUT treatment the reduction was about 70%. After treatment, both heavy metals analyzed (cadmium and lead) had such low concentrations in mortar samples that the leaching test results were inconclusive for comparative purposes.

Table 7: Results of chemical analysis of mortar samples (in ppm)

Substance\ Sample No.	23	24	22	21
Prior dredge material treatment	-	Echo	CUT and Echo	CUT and Echo after waiting period
Leachable Cyanide	1.22	0.82	0.44	0.41
Cadmium	ND < 0.02	ND < 0.02	ND < 0.02	ND < 0.02
Lead	ND < 0.01	ND < 0.01	ND < 0.01	ND < 0.01

ND - not detectable

6.3 Artificially Contaminated Dredge Material

A major concern for the development of effective dredge material treatment methods is the large variation of types and concentrations of the various contaminants. An effective treatment method cannot be developed and tested, unless samples with the largest possible amounts of specifically targeted contaminants are available. Because of the limited availability of suitable dredge material samples, worst-case scenarios were simulated by artificially contaminating the dredge material on hand. A useful side benefit of such "doping" is that it provides a relative benchmark for the leaching test method used by the Baron Consulting Company.

The test results presented in Section 6.2 showed that portland cement (CEM) is capable of containing heavy metals and other contaminants. In this Section, samples were produced in which gypsum (GYP) was used as the binder for comparison with those that used cement as the binder. In all cases, the dredge material was artificially contaminated with cadmium and lead by adding solved nitrates after drying (see Section 4). Mortar preparation was similar to that of concrete with treated dredge material (see Section 6.2). Aggregate-to-binder ratio was 3:1, and 20% dredge material substituted regular sand aggregate in all samples. The mixing procedure was the same as for samples 18 through 24 in Table 6 (new equipment, compare Section 6.2).

All compressive strength tests were performed with 1”x1” cylinders, which were used for leaching tests afterwards. Samples containing cement were cured, stored and tested following the rules introduced in the previous sections. Gypsum specimens were cured in room conditions and tested for compressive strength after two days. Unlike cement, gypsum undergoes a rapid and nearly complete hydration within the first 24 hours after mixing with water. All six cylinders prepared were tested at the same time because no further strength increase was expected. Strength test results are presented in Tables 8 (CEM) and 9 (GYP), whereas the leaching test results are given in Table 10.

Table 8: Test Plan and Results for Cement-Bound Mortar Cylinders

Sample No.	Sample Name	28 d density g/cm^3	7 d strength MPa	28 d strength MPa
Art 1	CEM DM	1.94	14.1	20.2
Art 2	CEM DMJ	1.96	20.8	31.3
Art 3	CEM DMCJ	1.93	19.0	28.7

Table 9: Test Plan and Results for Gypsum-Bound Mortar Cylinders

Sample No.	Sample Name	2d density g/cm^3	2d strength MPa
Art 4	GYP DM	1.70	4.9
Art 5	GYP DMJ	1.95	3.3
Art 6	GYP DMCJ	1.91	4.8

Compared with concrete containing regular DM samples with artificially contaminated DM exhibit a drop in compressive strength. After treatment with either Echo chemical (J) or the combination of CUT powder and Echo chemical (CJ), samples showed a slight increase of strength (Figure 31).

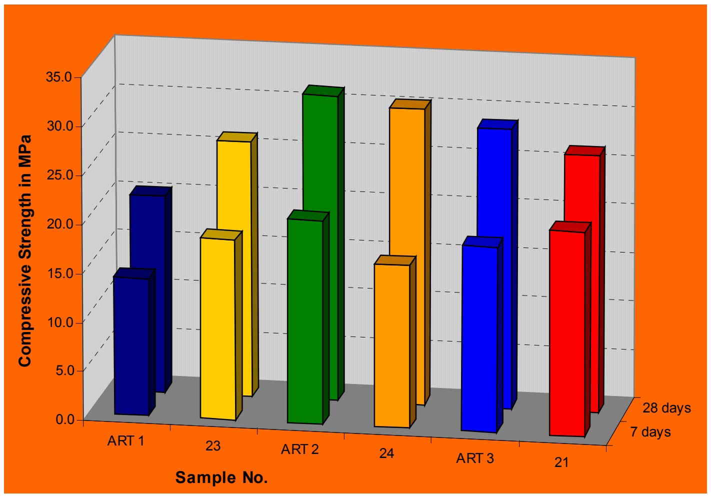


Figure 31: Compressive Strength of 1"x1"-mortar cylinders after 7 and 28 days (samples 23, 24, and 21 [Table 6] *and Art 1, Art 2, and Art 3* [Table 8]*)*

The densities after 28 days confirm these trends, exhibiting a negative correlation, i.e. the density decreased for natural DM and increased for treated DM after artificial contamination (compare Tables 6 and 8). The influence of additional lead and cadmium on the mechanical properties seems to be rather small.

Table 10: Results of chemical analysis of samples with artificially contaminated dredge material (in ppm)

Substance / Sample	Leachable Cyanide	Cadmium	Lead
DM	0.98	5.0	0.85
CEM DM	1.85	ND < 0.02	ND < 0.01
CEM DMJ	0.69	ND < 0.02	ND < 0.01
CEM DMCJ	0.36	ND < 0.02	ND < 0.01
GYP DM	0.70	1.15	0.70
GYP DMJ	0.24	0.94	0.75
GYP DMCJ	0.53	0.05	ND < 0.01

ND - not detectable

Gypsum samples show slightly lower densities and, as expected, a far lower strength than cement-bound mortars (Tables 8 and 9). The leaching test results of Table 10 prove the effectiveness of the treatment methods for heavy metals. For both binders the effectiveness was in the following order: 3) treatment with just the binder, 2) treatment with binder and Echo chemical, 1) treatment with binder, Echo chemical and CUT powder. The exception is leachable cyanide in sample GYP DMCJ. However, in this case there was an elevated concentration in the cement-bound mortar when compared to the artificially contaminated dredge material (DM and CEM DM in Table 10).

As also suggested in Tables 5 and 7, the heavy metal and cyanide contamination can be most efficiently decreased by the combined treatment, and Table 10 proves the effectiveness of cement in containing heavy metals. While neither cadmium nor lead could be detected in the cement-bound samples, this was not the case with gypsum.

In conclusion, the treatment methods proposed herein seem to be promising. Cement offers great benefits not only as one of the main components in concrete, responsible for strengthening and hardening processes, but also as treatment agent for pollutants. However, the low concentrations of contaminants found in any of the leaching tests are still too small to draw final conclusions.

7 Discussion and Outlook

Dredging is expected to remain a necessary operation to maintain navigational access to ports and shipping channels. As storage capacities for disposal of this potentially hazardous material are becoming scarce, the search for beneficial uses of dredge material is gaining urgency. The need for environmentally acceptable yet economical solutions is not only limited to the Port of New York and New Jersey. Worldwide, major ports have to face the same problem.

The research reported herein focuses on but is not limited to the use of dredge material as a constituent of concrete. The results obtained so far are promising in that they point towards practicable and efficient treatment procedures. Active decontamination can be achieved by the Columbia (CUT) treatment alone or in combination with the Echo chemical in order to prepare dredge material for further beneficial uses.

The treatment methods introduced in this report differ from most other proposed methods because of their simplicity, speed, cost efficiency, and usability of treated dredge material for further beneficial use. Complete decontamination as offered by vitrification, melting or thermal desorption carries a cost in form of energy consumption. Chemical treatments, such as stabilization, solidification, and washing, either prepare dredge material only for secondary beneficial use or are limited in their objectives, such as volume reduction, without directly targeting beneficial use. As a result, such decontamination is often rather incomplete.

Dilution techniques simply lower the concentrations of pollutants below acceptable levels and therefore cannot be considered as decontamination techniques. Bioremediation is time-, and if not placed in-situ, also space-consuming. In general, the more effective detoxification methods are more costly, and more environmentally friendly methods require long time. The approach we offer is comparatively fast and effective, but for large-scale application benefits and disadvantages are still to be demonstrated.

The leaching tests conducted so far have shown the effectiveness of decontaminating the actual dredge material samples. More definite conclusions can only be drawn from more highly polluted samples. Obtaining samples containing high levels of specific pollutants is difficult because of the random occurrence of such pollution. Therefore, dredge material was artificially contaminated with lead and cadmium. However, differences in behavior are expected between artificially contaminated and original polluted dredge material, which underwent weathering processes and was adapted to specific site conditions over time. Thus, the comparison between those two materials is qualitative in nature and not absolute.

As documented in Section 6.3, the combined treatment with Echo chemical and CUT powder is most effective. After binding dredge material with cement, neither cadmium nor lead could be detected in leaching tests. Since both are representative of heavy metals, our treatment methods should be considered effective for this category of pollutants.

Gypsum seems to be less effective for decontamination. The addition of sulfates during the preparation of dredge material for further use in concrete applications increases the risk of delayed concrete damage or failure (e.g., secondary ettringite formation). Hence, gypsum does not appear to be suitable for decontamination of dredge material in combination with utilization in concrete products.

When used as constituent of concrete, dredge material can replace part of the aggregate without overly reducing the concrete strength. This conclusion is valid not only for treated but also for "natural" dredge material. The workability however, limits the amount of dredge material that may be used, and it remains to be shown to what extent the dredge material can affect the cement hydration. The mixing equipment had to be modified to satisfy the special needs of mixing mortar that contains dredge material.

The treatment procedures for concrete applications introduced herein can be divided into two categories. In the first method all decontamination processes take place within a short time span, whereas the second method permits the treated material to dry out, which results in a powder that can easily be distributed within the concrete just like regular components. Further studies will optimize this procedure, especially in conjunction with the use of superplasticizers, which increase the workability for comparable water-to-binder ratios.

Long-term studies of durability issues still need to be conducted. The research will also consider the use of dredge material as filler. Because of its particle size distribution dredge material seems to be suitable for filling voids between regular concrete components. It is planned to use a stabilizer as additional filler, which is capable after a certain time to absorb contaminants. There may be an optimum amount of such a stabilizer to maximize detoxification and yet obtain material with adequate mechanical properties.

So far, the replacement of around 10M-% regular sand aggregate with dredge material seems to define an acceptable compromise between strength, density, workability, and leaching performance. This translates into an amount of 6M-% of all concrete components. When used as filler, we hope to increase the percentage of dredge material up to 12M-%. These amounts appear to be disappointingly low but represent the initial outcome of our efforts to date. We have high hopes that our research will eventually lead to treatment procedures that permit the utilization of larger amounts of dredge material.

Due to the variability of material properties, treatment methods have to be designed for the worst-case scenario. Hence, extremely high concentrations of the various contaminants have to be considered the standard throughout the development of suitable treatment procedures. If such concentrations cannot be found in actual dredge material, they need to be simulated.

Further research has to address the questions of how and why the various contaminants influence the properties of either the untreated or treated dredge material and what limitations they impose on beneficial uses. For example, does the presence of excessive amounts of PCB prohibit further use? Do specific contaminants require modifications of proposed treatment methods or call for the development of alternative methods? Or does there exist a treatment method that is effective in containing all potential contaminants, yet still results in a material suitable for further use?

The promising first test results and the potential benefits of the new treatment methods under development will continue to define an exciting challenge. It is hoped that this work will eventually lead to an ecologically and economically acceptable solution of the dredge material problem, by transforming a highly contaminated waste material into a value-added resource.

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Appendices Detailed Test Results