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MDPI

Review

A Review of Beneficial Use and Management of Dredged Material

Pranshoo Solanki [1,*], Bhupesh Jain [2], Xi Hu [3] and Gaurav Sancheti [4]

1 Professor of Construction Management, Department of Technology, Illinois State University, Campus Box 5100, Normal, IL 61790, USA
2 Research Scholar, Department of Civil Engineering, Manipal University Jaipur, Jaipur 303007, India; bhupesh.199105602@muj.manipal.edu
3 Doctoral Student, Department of Civil and Environmental Engineering, New Jersey Institute of Technology, Newark, NJ 07102, USA; xh32@njit.edu
4 Associate Professor, Department of Civil Engineering, Manipal University Jaipur, Jaipur 303007, India; gaurav.sancheti@jaipur.manipal.edu
* Correspondence: psolanki@ilstu.edu; Tel.: +1-3095382696

Abstract: This study systematically examined dredged materials from various aspects, including their sources, the volume generated annually, beneficial uses, and the management processes currently practiced. In addition, this paper presents the relevant policies governing the dredging, reuse, and disposal of dredged materials in the United States. A summary of various sources, types/classifications, and the physical and chemical properties of dredged materials used by various researchers are presented. This paper also summarizes the innovative techniques for the beneficial reuse of dredged materials in a wide range of applications in concrete materials, construction products, roadway construction, habitat building, landfill liner/cap, agriculture soil reconstruction, and beach nourishment. Further, limitations and corresponding solutions related to the beneficial use and management of dredged materials were provided in the end.

Keywords: dredged; stabilization; heavy metals; concrete; habitat; agriculture; landfill

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1. Introduction

Dredging sediment deposited in waterways is a critical operation to maintain and improve the global and national water navigation, recreation, and defense systems [1,2]. Additionally, this operation is of great significance for flood prevention by reducing sea levels [3] and providing material to build coastal protection [4]. The sediment excavated from waterbodies, including waterways and harbors, through dredging activities, is recognized as dredged materials (DM). DM is composed of different-sized solid particles with a high natural moisture content. In terms of the DM's physical and chemical properties, it is significantly different from the quarry sand used for construction due to its content of not only salt but the presence of heavy metals and organic matter [5].

According to the United States Army Corps of Engineers (USACE), the average annual quantity of material removed from waterways and channels in the United States is approximately 212 million yd^3 (152 million m^3) during fiscal years 2008–2012 [6]. Figure 1 shows the estimates of the average cubic yardage dredged by USACE district categorized by class of work (maintenance and new work) during fiscal years 2008–2012. Over 95% of the materials dredged are a clean and viable resource that can be used productively if placed in proper locations [6]. Dredging in the United States encompasses more than 400 ports, over 200 deep water harbors, and 25,000 miles (40,234 km) of navigation channels [7]. In many countries, DM is regulated as a waste material or controlled fill. In most countries, only about 10% of dredged materials were reused, and 90% were either dumped into the sea or used for land reclamation [5,8,9]. Currently, as shown in Figure 1, the most common practice of disposing of DM in the US is by means of dumping it into ocean waters at appropriate sites approved by the United States Environmental Protection Agency (EPA) or placing it in several locations such as uplands and nearshore confined disposal facilities (CDFs) beach replenishment, sites to create wetlands, and river sandbars and islands [6]. Nevertheless, there is an outdated perception that this type of practice has an apparent weakness of not being sustainable and safe for local environments [10–13]. For instance, DM from contaminated industrial locations can have negative environmental impacts on the disposal locations and surrounding areas through the diffusion of contaminants such as heavy metals (arsenic, cadmium, mercury, etc.) and toxic substances generated from organometallic interactions into soils and groundwater [13].

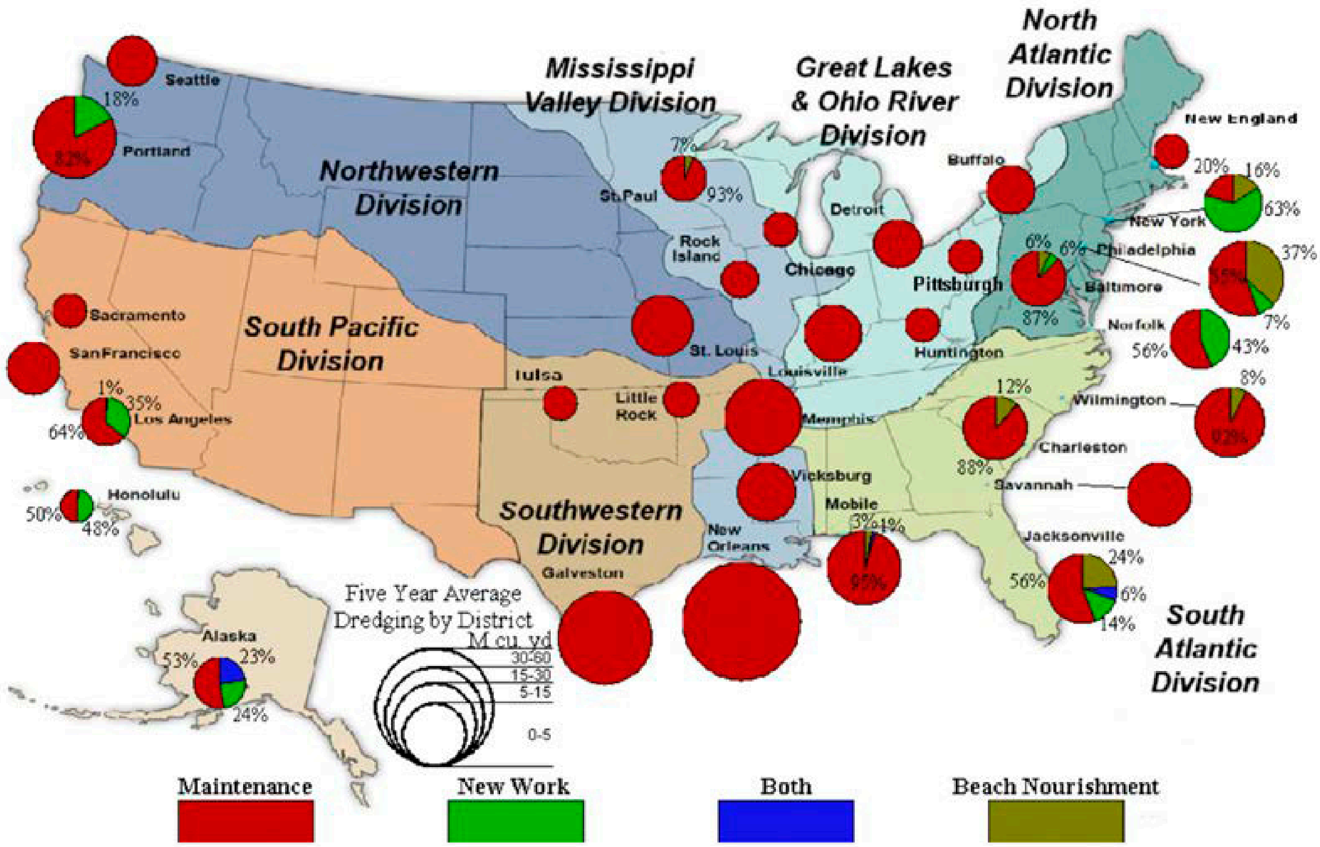

Figure 1. DM disposal site in the United States [6].

Various literature reviews have shown that most research has been conducted or completed exploring the techniques for recycling DM. However, only a few scholastic reviews comprehensively or systematically recorded the practices of beneficial utilization of DM in the U.S. To maximize the beneficial use of DM and obtain more environmentally sustainable solutions in the U.S. and the global community, the implementation of enhanced DM management practices is urgently required.

The primary objective of this study was to investigate the beneficial use and current DM management practices through a wide literature review. Specifically, the types and sources, beneficial uses, management strategies of DM, and relevant policies related to its beneficial use are summarized in this review. Further, based on the reviewed literature, the practical challenges/limitations of the current use of DM, tips/resources to help communities be involved with its beneficial use, and future work addressed.

2. Dredged Material

DM can be defined as fine sediment from the wear or erosion of land since dredged materials are sedimentsfrom dredging rivers, marine operations, and continental watercourses [14]. According to the Minnesota Pollution Control Agency (MPCA), DM can also be viewed as material excavated at or below the ordinary high-water level of water basins, watercourses, public waters, or public wetlands. As shown in Figure 2, the DM consists of a mixture of solid particles, organic/inorganic matter, contaminants (heavy metals and toxic substances), and a high content of liquid (interstitial water). Specifically, the solid particles include sand, silt, clay, and shells. Moreover, heavy metals (e.g., mercury, cadmium, arsenic, etc.) and toxic substances (e.g., benzene, dioxins, pesticides, naphthalene, etc.) have also been found in DM [15]. A study by USEPA in 1991 [15] revealed that excessive sedimentation may become problematic due to blanketing the bottom of an aquatic ecosystem, causing environmental damage and reducing the draft needed for shipping. Further, accumulated contaminants can endanger human and ecosystem health. Therefore, for effective management of DM in the U.S. and global community, it is significantly important to specify the sources and categories of DM prior to implementing relevant technological or managerial practices to place or beneficially reuse it.

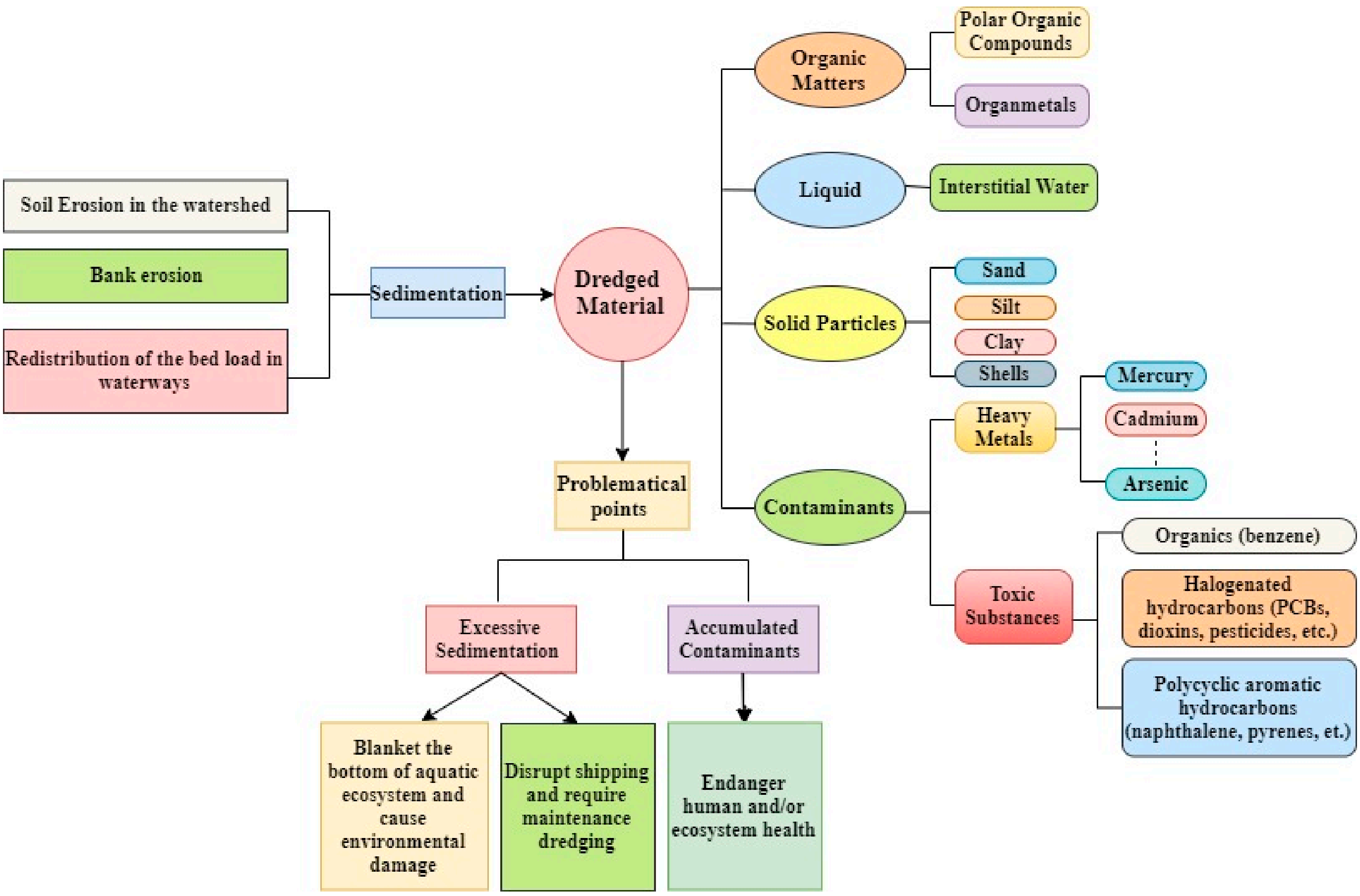

Figure 2. Dredged material sources, characteristics, and social/ecological problems.

2.1. Sources

The sources of sediments can be categorized into two groups, namely, natural formation and sedimentation and dredging. The origins of DM sediments are based on several categories of natural processes, including soil erosion in the waterbed, bed erosion, and redistribution of the bed load in waterways [15,16]. Further, DM sediments can be obtained from authorized improvements such as the construction and dredging of waterways/channels, harbors, turning basins, locks and dams, dikes, jetties, breakwaters, docks, and berthing areas [6]. Table 1 [15–25] illustrates that the weathering and erosion of soil are the main sources of sediments, but organic materials and bank erosion also have diversified the sources of sediments [15,18,19,26]. The main difference between dredged materials and terrestrial soils is the source. They consist of different mixtures of the same basic materials, namely sand, silt, and clay. Rivers naturally sort the materials by size fraction. As a result, the dredged materials are frequently more uniform and better sorted. Gravel is usually obtained from the mouth of tributaries. Sources of sea sediments include rocks and soil particles transported from land areas as well as the remains of marine organisms, organic matter, chemical precipitates from seawater, and even materials from outer space [21–23,25]. To obtain sediments from either land or marine areas, appropriate dredging techniques, such as coring, grab, and suction dredging, are usually applied. Specifically, hydraulic suction dredging is commonly used to dredge sediments on a large scale [27]. Coring and grab sampling methods are widely introduced for conducting tests or chemical and toxicological analyses of dredged sediments [15,24,28,29].

Table 1. Sources of DM.

Sources	Attribute	Description	References
Natural Formation and Sedimentation	Land Areas	Soil erosion in the waterbed, band erosion, and redistribution of the bedload in the waterways.	[15]
Natural Formation and Sedimentation	Land Areas	Weathering and erosion of minerals, organic material, soil in upstream areas, and riverbanks.	[16]
Natural Formation and Sedimentation	Land Areas	Mud, sand, and silt that accumulate in navigable channels, bay inlets, and marinas from the erosion of upstream sediments.	[17]
Natural Formation and Sedimentation	Land Areas	Soil erosion from uplands and hillslopes, as well as infrequent events such as mass wasting and erosion from areas affected by fire; streambank erosion in the stream corridor.	[18]
Natural Formation and Sedimentation	Land Areas	Sheet, rill, and gully erosion from upland; ravine, bluff, and streambank erosion near channels.	[19]
Natural Formation and Sedimentation	Marine Areas	Rocks and soil particles transported from land areas, as well as the remains of marine organisms, products of submarine volcanism, chemical precipitates from seawater, and materials from outer space that accumulate on the seafloor.	[20]
Natural Formation and Sedimentation	Marine Areas	A mixture of material deposited on the seafloor that originated from the erosion of continents, volcanism, biological productivity, hydrothermal vents, and/or cosmic debris.	[21]
Natural Formation and Sedimentation	Marine Areas	Deposits accumulating below the sea, including debris from weathering and erosion on land, organisms, organic matter, minerals precipitated from seawater and volcanic products such as ash and pumice.	[22]
Artificial Dredging	Coring	Use a plunger to extract sediments and their faunas from open marine, estuarine, and limnic environments for performing tests on dredged material.	[7,18,23]
Artificial Dredging	Grab	A more ideal way to collect fine-grained cohesive sediments, such as silt and clay, than noncohesive sands, comminuted shells, and gravel from a variety of aquatic environments for chemical and toxicological analyses of sediments or other purposes.	[18,24]
Artificial Dredging	Suction	The most commonly used method to dredge sediments on a large scale	[25]

2.2. Types and Classification

Sediments are based on several categories. As shown in Table 2 [28–35], two classification standards, including particle size (texture) and composition (formation), are commonly used. Initially, Wentworth, in 1922, standardized the definitions of sediment using four size fractions, namely, gravel (dn > 2 mm), sand (62.5 µm< dn < 2 mm), silt (4 µm < dn < 62.5 µm), and clay (dn < 4 µm). Of those, dn represents the nominal diameter of particles in sediment samples [32]. Shepard's Classification Scheme in 1954 [33] and Folk's Classification Scheme [30] were, respectively, raised to classify sediments, as these were more detailed in nature [30,33,36,37]. It is worth pointing out that Shepard's methods emphasized the relative ratios of sand, silt, clay, and gravel (he eventually modified the scheme because gravel was not considered in the original scheme) within a sediment sample using a ternary diagram [38]. Beyond that, relying on two triangular diagrams with 21 major categories of sediments, Folk proposed the use of the term mud to define silt plus clay but placed an emphasis on gravel because its concentration is a function of the highest current velocity at the time of deposition [38]. In comparison, the composition/formation-based classification standard is more related to the sources of sediments, especially marine sediments. In this way, sediments can be classified into four types: lithogenous, biogenous, hydrogenous, and cosmogenous [22]. For example, terrigenous and red clay, remnants of organisms such as shells, chemical/mineral precipitates from the water, and cosmogenic materials may contribute a small to a large percentage of the composition of lithogenous, biogenous, hydrogenous, and cosmogenous sediments.

Table 2. Classification of the sediments.

Classification Standard	Attribute		Description	Emphasis	References
Particle Size (Texture)	Wentworth Grade Scale		Standardized definitions of the fractions. Gravel (d_n > 2 mm); sand (62.5 um< d_n < 2 mm); silt (4 um <d_n< 62.5 um); clay (d_n < 4 um).		[28]
	Shepard's Classification Scheme	Original	A single ternary diagram with sand, silt, and clay to graphically show the relative proportions among them within a sample.	The ratios of sand, silt, and clay	[29,30]
		Modified	Addition of a second ternary diagram to account for the gravel fraction.		[31]
	Folk's Classification Scheme		Two triangular diagrams with 21 major categories and uses the term mud (defined as silt plus clay).	Gravel	[30,32,33]
Composition/ Formation	Lithogenous		Sediments from the land form through the weathering process (terrigenous and red clay).		[34,35]
	Biogenous		Remnants of organisms that refused to be dissolved (shells).		
	Hydrogenous		Chemical precipitates or minerals solidified out of ocean water.		
	Cosmogenous		Materials such as meteorites or asteroids from outer space.		

d_n represents the nominal diameter of fractions in sediments.

2.3. Chemical Composition

A summary of the chemical compositions of different DM reported by various researchers is presented in Table 3. It is evident from Table 3 that, in general, DM mainly consists of silica (SiO_2) followed by alumina (Al_2O_3), calcium oxide (CaO), and iron oxide (Fe_2O_3). A few studies reported a very high content of CaO and Fe_2O_3. For example, Limeira et al. [5] reported 64.5% of CaO in DM, followed by 19% of SiO_2 and 5.6% of Al_2O_3. Further traces of alkalis in DM are also present in Table 3. A summary of heavy metal concentrations in DM reported by various studies is presented in Table 4. High concentrations (>5 mg/kg or 5 mg/L) of copper (Cu), arsenic (As), lead (Pb), chromium (Cr), zinc (Zn), and nickel (Ni) are recorded in Table 4. Further, different sources of DM contain varying percentages of heavy metals, as shown in Table 4. Hence, permissible limits of heavy metal should be checked and compared to regulation standards before using DM or using a suitable method to treat DM before its applications, as mentioned in Table 4.

Table 3. Chemical composition of dredged material.

Source	SiO_2	Al_2O_3	CaO	Fe_2O_3	Na_2O	K_2O	MgO	MnO	TiO_2	P_2O_5	SO_3	Cl	Cr_2O_7	LOI
[39]	44.17	14.18	12.17	4.72	4.70	3.84	2.617	0.08	0.50	-	-	-	-	-
[40]	50.48	14.89	14.39		1.40	2.04	5.89	-	0.79	0.24	1.93	1.43	0.05	-
[41]	71.0	10.1	2.6	3.8	4.5	3.4	-	0.1	0.8	0.1	0.1	0.6	-	3.6
[42]	45	4.1	25	0.5	-	-	0.3	-	-	-	0.001	1.7	-	-
[5]	19.0	5.6	64.5	3.7	0.1	0.9	2.0	-	-	-	3.2	-		1
[37]	53.48	25.91	0.93	9.41	0.49	3.81	2.12	0.11	1.16	0.14	-	-	-	1.99
	54.48	24.37	1.57	8.01	1.04	2.89	1.82	0.14	1.05	0.39	-	-	-	3.43
	52.96	21.69	2.22	11.64	0.63	4.13	1.58	0.21	1.33	0.55	-	-	-	2.22
[43]	70.11	11.76	0.91	4.89	1.26	1.76	0.89	-	0.87	-	-	-	-	4.5
[44]	56.65	15.31	5.37	6.15	1.25	1.54	2.67	-	-	-	2.05	-	-	-
[45]	56.87	22.93	-	10.79	0.33	2.66	-	-	-	-	-	-	-	-
[46]	58.3	8.8	14.7	3.6	1.3	1.5	2.6	0.2	0.5	0.3	2.2	0.1	-	18.9
[9]	57.8	18.7	2.05	7.67	2.05	3.93	2.64	0.07	-	0.28	1.95	-	-	6.6
[47]	63.09	16.76	2.59	7.95	-	2.37	5.49	0.20	1.04	0.20	-	-	-	-
[48]	71.0	10.1	2.6	3.8	1.4	3.4	1.1	0.1	0.8	0.1	1.0	-	0.1	3.6
[40]	61.92	15.09	9.56	3.55	1.71	2.63	2.52	0.08	0.63	0.19	0.92	0.91	-	<2.3
	34.87	5.79	27.10	7.08	0.78	0.42	20.63	0.14	0.27	0.09	0.76	1.75	0.159	4.11
	53.24	18.33	8.93	6.45	1.50	2.30	4.01	0.20	1.19	0.30	1.26	1.91	0.049	4.72
	47.31	14.40	17.54	6.43	1.52	2.11	5.28	0.15	0.77	0.21	2.85	1.23	0.064	4.19

Table 4. Heavy metals in dredged material.

Concentration Unit	Cd	Cu	As	Hg	Pb	Cr	Zn	Ni	References
mg/kg	1	22.87	6.80	0.557	15.93	-	81.60	34.50	[37]
	1	5.70	7.13	0.242	14.43	-	76.30	7.80	
	1	18.97	5.97	0.227	47.20	-	93.30	19.07	

Table 4. *Cont.*

Concentration Unit	Cd	Cu	As	Hg	Pb	Cr	Zn	Ni	References
mg/kg	<0.1	15.2	7.9	0.3	11.8	85	42	37.3	[39]
	0.1	17.4	8.43	<0.01	5.64	905	34.8	687	
	0.43	23	347	2.33	13	140	128	132	
	0.17	46	12.80	0.09	35.4	111	77	55	
	0.08	-	-	1.64	42.24	34.16	390.8	342.5	[42]
	0.16	-	-	1.02	89.65	118.3	335.5	9.6	
mg/kg	<0.05	-	<0.05	-	<0.25	<0.05	-	<0.05	[49]
mg/kg	0.68	0.8	0.2	-	1.92	0.9	12.9	0.2	[50]
mg/kg (dry)	15.3	-	-	-	823	196.9	2532	-	[51]
	38	-	-	-	1143	218	5438	-	
mg/kg	<0.42	27	18.03	0.18	39	44	151	25	[52]
mg/kg	<0.1	<0.5	<0.5	<0.01	<1	<0.1	<0.5	<0.4	[53]
mg/kg	<0.1	15.2	7.9	0.3	11.8	85	42	37.3	[40]
	0.1	17.4	8.43	<0.01	5.64	905	34.8	687	
	0.43	23	347	2.33	13	140	128	132	
	0.17	46	12.80	0.09	35.4	111	77	55	

3. Policy Related to Beneficial Use

Table 5 summarizes relevant federal and/or state-level policies in the U.S. that (1) regulate the operation and management of DM and (2) govern the activities contributing to the formation of DM. For example, The Clean Water Act (CWA) establishes the fundamental baseline for supporting both the administration of the discharges of pollutants into waters and regulating the quality of surface waters. The National Environmental Policy Act (NEPA) requires all federal agencies to evaluate the environmental effects before undertaking any proposed action (e.g., dredging materials from rivers) to eliminate destruction to the environment and biosphere. The Endangered Species Act (ESA) aims to conserve threatened and endangered species (e.g., plants and animals) and their habitats, ensuring that human activities such as dredging materials from seabed or wetlands will not cause threats to the survival of species and their habitats. The Resource Conservation and Recovery Act (RCRA) regulates the disposal of municipal and industrial waste to (1) protect civilians and the natural environment from the potential hazards of such waste and (2) ensure the management of waste has been conducted in a proper manner. The Toxic Substances Control Act (TSCA) governs the manufacturing and distribution of new or existing chemicals that may form hazardous waste. The Coastal Zone Management Act (CZMA) was established for the protection and restoration of the nation's coastal resources, such as DM from the Great Lakes.

In addition to the regulations as presented in Table 5, as per the Minnesota Pollution Control Agency (MPCA), the use/reuse of dredged material can be categorized into three management levels: level 1, level 2, and level 3, based on sediment characterization of DM. Level 1 is applicable to the use/reuse of DM for residential or recreational properties. The sediment characterization of DM that meets level 1 management is subjected to be at or below the values as shown in the column "Level 1 Soil Reference Value (SRV)" of Table 6. Level 2 is suitable for the use/reuse of DM for industrial properties. As also shown in Table 6, the sediment characterization of level 2 DM shall meet the quantitative requirements in the column "Level 2 Soil Reference Value (SRV)." Level 3 indicates that DM is not suitable for use or reuse due to significant contamination [54].

Table 5. Policies related to dredged material in the US.

	Name of Policies	Description
1	Clean Water Act (CWA)	Regulates discharge of pollutants into the waters (use of dredged material for artificial reef and berm development).
2	National Environmental Policy Act (NEPA)	Environmental effects of proposed Federal agency actions (20 years dredged material management plan for the Calumet River and Harbor).
3	Endangered Species Act (ESA)	For protecting imperiled species (to conduct any new or maintenance activity or project that may require a permit).
4	Resource Conservation and Recovery Act (RCRA)	Proper management of hazardous and non-hazardous solid waste (regarding the handling, transport, and disposal of wastes).
5	Toxic Substances Control Act (TSCA)	Regulates the introduction of new or already existing chemicals (regarding the handling, transport, and disposal of wastes).
6	Coastal Zone Management Act (CZMA)	Develop and implement coastal zone management plans.

Table 6. Dredged material soil reference values [54].

Parameter	Level 1 Soil Reference Value (SRV) (mg/kg, Dry Weight)	Level 2 Soil Reference Value (SRV) (mg/kg, Dry Weight)
	Inorganic Metals	
Arsenic	9	20
Cadmium	25	200
Chromium III	44,000	100,000
Chromium VI	87	650
Copper	100	9000
Lead	300	700
Mercury	0.5	1.5
Nickel	560	2500
Selenium	160	1300
Zinc	8700	75,000
Barium	1100	18,000
Cyanide	60	5000
Manganese	3600	8100
	Organics	
PCBs (Total)	1.2	8
Aldrin	1	2
Chlordane	13	74
Endrin	8	56
Dieldrin	0.8	2
Heptachlor	2	3.5
Lindane (Gamma BHC)	9	15
DDT	15	88
DDD	56	125
DDE	40	80
Toxaphene	13	28

Table 6. *Cont.*

Parameter	Level 1 Soil Reference Value (SRV) (mg/kg, Dry Weight)	Level 2 Soil Reference Value (SRV) (mg/kg, Dry Weight)
2,3,7,8-dioxin, 2,3,7,8-furan and 15 2,3,7,8-substituted dioxin and furan congeners	0.00002	0.000035
Polycyclic Aromatic Hydrocarbons (PAHs)		
Quinoline	4	7
Naphthalene	10	28
Pyrene	890	5800
Fluorene	850	4120
Acenaphthene	1200	5260
Anthracene	7800	45,400
Fluoranthene	1080	6800
Benzo (a)pyrene (BAP)/BAP equivalent	2	3
* Benzo (a) anthracene	* Dibenz (a,h) anthracene	* 3-Methylcholanthrene
* Benzo (b) fluoranthene	* 7H-Dibenzo (c,g) carbazole	* 5-Methylchrysene
* Benzo (j) fluoranthene	* Dibenzo (a,e) Pyrene	* 5-Nitroacenaphthene
* Benzo (k) fluoranthene	* Dibenzo (a,h) Pyrene	* 1-Nitropyrene
* Benzo (a) pyrene	* Dibenzo (a,i) Pyrene	* 6-Nitrochrysene
* Chrysene	* Dibenzo (a,l) Pyrene	* 2-Nitrofluorene
* Dibenz (a,j) acridine	* 1,6-Dinitropyrene	* 4-Nitropyrene
* Dibenz (a,h) acridine	* 1,8-Dinitropyrene	
* 7,12-Dimethylbenz[a]anthrancene	* Indeno (1,2, 3-cd) pyrene	

* The results for these analytes should be added together and treated as the BAP equivalent, compared against the soil reference value for benzo (a) pyrene above.

4. Beneficial Uses

Due to the existence of salts, heavy metals, and organic matter in contaminated DM, direct reuse in construction may lead to corrosion of reinforcement and chloride attack [40,55,56]. Therefore, relevant treatment techniques such as the stabilization of heavy metals and organic thermal elimination should be applied before their reuse in construction activities or other beneficial uses [16]. A summary of various beneficial uses of DM is discussed in subsequent sections.

4.1. Concrete Materials

Most aggregates used for producing concrete are retrieved from quarries or alluvial rivers. However, these natural resources are being depleted, and their exploitation can result in harm to the environment [5,57] if not sustainably implemented. Aggregates sold or used for construction in the US reached an annual average of approximately 2.18 billion metric tons from 2007 to 2016 (Figure 3a) [38,43], including 90 million metric tons of sand and gravel and 1.28 billion metric tons of crushed stone. The total commercial value of the aggregates sold or used has an annual average of $19.45 billion (sand and gravel: $6.90 billion; crushed stone: $12.55 billion) each year from 2007 to 2016 (Figure 3b). Due to the loss of data in Delaware and Louisiana, the quantity and total value of the crushed stone sold or used in these two states were not included [43].

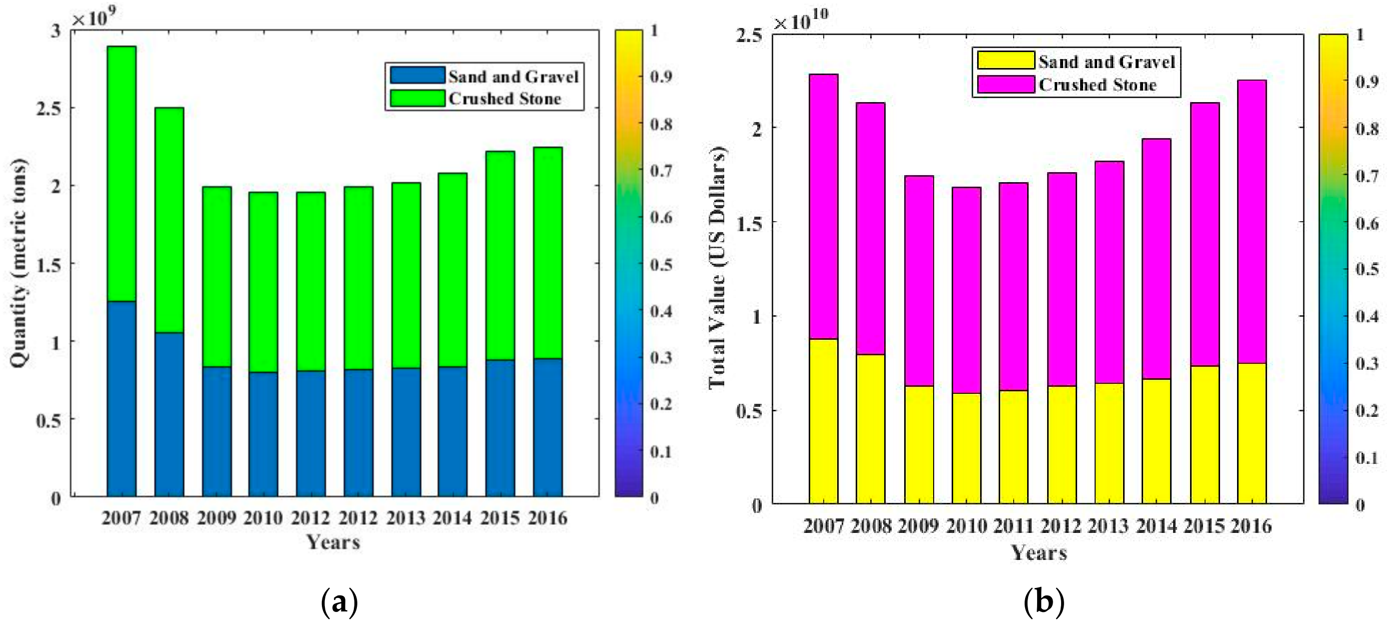

Figure 3. Aggregates annually sold or used in the United States from 2007 to 2016: (**a**) quantity in metric tons; (**b**) total value in US dollars [43].

Cement production also requires other natural resources, such as limestone and shale (or clay). The continuous excavation of raw materials such as limestone is also accelerating the depletion of natural minerals. According to the USGS report, in 2019, 86 million metric tons of Portland cement was produced in the U.S. Also, the sales of cement in that single year were valued at $12.5 billion [43].

Due to the multiple natural sources of sediments, some commonly used materials, such as sand for concrete and clay for cement production, can also be found in DM. Therefore, economically, there is a huge potential to use DM to partially or fully replace terrestrial aggregates or cement for producing concrete where it can be accessed. Correspondingly, a series of studies have been conducted to expand the scope using DM as concrete materials. Based on the review of the relevant literature, DM was commonly used as a substitute for sand or cementitious material (cement) in concrete.

4.1.1. Sand Substitute

A summary of studies carried out by different researchers using DM as a sand substitute is presented in Table 7. Ozer-Erdogan [51] replaced natural sand with DM up to 100% by adding some Supplementary Materials. Dredged marine sand obtained from the port of Barcelona was used to replace 15% to 50% fine aggregate. Limeira [5] was able to demonstrate a 14% increase in the strength of the material when they used a 50% replacement of materials). A study from a Turkish port/harbor revealed that DM could replace sand up to 50% without any treatment, and after treatment, 100% replacement is possible in ready-mix concrete [51]. If the chloride content in DM is less than 0.18% or the total chloride content in concrete is less than 0.34%, concrete can be called safe against reinforcement corrosion [52]. Self-consolidating lightweight aggregate concrete made from DM taken from the A-Kung-Diann reservoir in southern Taiwan showed acceptable strength and durability properties. The density of lightweight aggregate was around 800 kg/m^3. Reduced chloride penetration, cracking, and weight loss were recorded as the water-to-binder ratio decreased [42].

Table 7. Summary of reviewed studies for use of dredged material as a sand substitute.

Sources	Replacement Description	Supplementary Material	Optimum Result	Treatment	Outcome	Source
Port of Barcelona	0%, 15%, 25%, 35%, 50%	Rapid-hardening type II cement, plasticizer	50% replacement	No pre-treatment	Greater compressive and flexural strength than the control mix.	[5]
Turkish ports/harbors	0%, 25%, 50%, 75%, 100%	Superplasticizer	≤50% for untreated DM, 100% for treated DM	Sieving Oven drying washing	Cl^{-1}, SO_4^{2-}, TDS, Cr, and Sb beyond the limits of Class III (Inert waste) landfilling criteria; hence, treatment is required.	[40]
China	Chloride content in DM ranges from 0 to 1.07%.	Fosroc polycarboxylates (superplasticizer)	Safe from corrosion if chloride content in DM is less than 0.18% and total chloride in concrete is <0.34%.	-	-	[56]
A-Kung-Diann Reservoir in southern Taiwan	100% replacement of coarse and fine aggregate	Fly ash, slag, superplasticizer	Optimum strength and durability achieved at 0.28 w/b ratio.	Drying, sieving, sintering	Density of DM aggregate obtained is 800 kg/m^3 and 1060 kg/m^3.	[45]
Port of Bohai Bay in China	1% fumed silica and 1% polypropylene fiber	Fumed silica, polypropylene fiber	1% addition of fume gives the optimum result	No treatment	Granular modifier should be preferred over the fibrous modifier.	[57]
Kaohsiung Harbor, Taiwan	Mass ratio of dredged sediment(7–14), oxygen furnace slag (0–7) and glass waste (1)	Basic oxygen furnace slag, waste glass	Preheating at 500 °C and sintering at 1175 °C with sediment, oxygen furnace slag, and glass waste in the ratio of 10:4:1	Preheating (400–700 °C), sintering (1125–1200 °C)	If water-soluble chloride content is large, then it may reduce concrete strength and corrode the reinforcement.	[9]
Dianchi Lake in China,	-	Lime, phosphogypsum, fly ash, water glass, organosilicon solution, white glue	DM (80%), cement (3%), lime (3%), phosphogypsum (3%), fly ash (5%), and water glass (6%).	Crushing, pelletizing	A stable shell layer was extremely required for concrete made with lightweight aggregate to prevent crushing.	[43]
France	-	Phosphoric acid	14–17% shrinkage	Treated with phosphates and then calcination (1000 °C for 3 h)	Converting Pb, Cd, Zn, and Cu to insoluble metallic phosphates.	[51]

FA—Fine aggregate; CA—Coarse aggregate; UPVT—Ultrasonic pulse velocity test; CT—compressive strength test; TT—tensile strength test; WP—water penetration; ME—Modulus of elasticity; CS—Capillary suction; WA—water absorption test; LT—leaching test; RCPT—Rapid Chloride penetration test; MIP—mercury intrusion porosimetry test; FT—Flexural strength test; LOI—loss on ignition test; FT—Freezing and thawing test; AL—Atterberg's limit.

In a study from the Port of Bohai Bay in China, DM contained a high percentage of chloride. The addition of 1% silica fume increased the strength of the mix by 8.8%. Silica fume is a supplementary cementitious material that helps improve the strength of concrete. Also, porosity and electric flux were reduced by 33% and 24.5%, respectively. Further, the addition of polypropylene fiber reduced the strength and increased the porosity of the concrete. DM obtained from Kaohsiung harbor in Taiwan contained 1380 mg/kg of water-soluble chloride [47]. Sand prepared from this DM by preheating and the sintering process reduced water-soluble chloride by 99%. One of the studies in China crushed the dredged sediment and pelletized it with a water glass aqueous solution. The pelletized aggregate was coated with a waterproofing material or hard shell and used as lightweight aggregate [58]. In another study in France, treated DM with phosphoric acid converted heavy metals like Pb, Cd, Zn, and Cu into metal phosphates and then performed calcination to remove the organic content of DM. This is patented as the Novosol® Process [48].

4.1.2. Cement Substitute/Supplementary Cementitious Material

Marine DM is being successfully used as a partial cement substitute if it satisfies the permissible limit of heavy metals and leaching of harmful substituents. Researchers replaced up to 40% cement with treated/untreated DM [41,48,59]. The treatment process included washing, grinding, and calcination of DM. Calcination is the heating of solids to a high temperature to remove volatile substances, oxidize a portion of mass, or render them friable. Therefore, calcination is sometimes considered a process of purification. A few studies revealed that if the chloride or salt content in the DM is high, then it negatively affects the strength of cement-based material. Therefore, washing the DM is required [41,48]. Simply washing may reduce free chloride content by up to 80% [41,48]. Calcination after grinding at high temperature removed the organic matter present in DM and helped with the (or activate the clay minerals) activation of clay minerals. As the percentage of cement replacement increased, the strength of the mix was found to decrease [41,48,60]. However, 8% cement replacement with DM and limestone as filler showed strength within permissible limits. It was noted that the mechanical performance of mortar prepared by washed and calcinated DM at 650 °C was found to be better than the corresponding mortar prepared by using DM calcinated at 850 °C [48]. It can also be noted that as the chemical composition is different for different world areas, the results may vary accordingly.

In a study conducted in Singapore by Du and Pang [61], the marine clay was ground into a ball mill and then calcinated to activate clay minerals at different temperatures ranging from 600 °C to 800 °C. The results showed that the effect of temperature was not significant, and calcination at 600 °C gave the same result at 800 °C. It was noted during the study that when marine clay replaced cement, it produced better results compared to inert material like quartz. This behavior was attributed to the presence of 20% kaolinite in the marine clay, which showed pozzolanic activity after calcination [61].

DM collected from the Port of Oran, the Mediterranean Sea, contained a high percentage of salts and water, which was reduced by leaching and natural decantation process. Water content was reduced to 7% by the natural decantation process. Then, chemical treatment of DM with 3% phosphoric acid was conducted to trap heavy metals. Results showed that the replacement of 5% cement with DM in the mortar was not acceptable due to lower strength [41]. DM of the Ruzin Reservoir in Slovakia was activated mechanically by dry milling and chemically by grinding it with NaOH. Mechanically activated means to reduce the size of particles so that more surface area is available for chemical reaction. After a 40% replacement of cement with mechanically activated dredged material, the results showed a better compressive strength for 28 days compared to chemically activated DM. However, 28-day flexural strength results revealed chemically activated DM comparable to mechanically activated DM. Further, both compressive and flexural strength after 40% replacement were found to be lower than the control mix [60].

4.2. Construction Products

4.2.1. Composite Material

Recently, methods have been developed to beneficially reuse DM in producing composite materials [9,42,53,58,62–66]. The new composites can be used to produce construction products such as tiles, bricks, and blocks, as summarized in Table 8. Composite material containing 50–60% DM by weight as the principal component with the utilization of sediments dredged from Brazilian seaports. This composite material showed and continues to show promising potential for producing conventional bricks, blocks, etc. Moreover, construction and demolition debris (20–35% by weight) and lime production wastes (15–30% by weight) were also included as the other two components in this composite. The compressive strength results revealed that this type of composite can reach 6.3 MPa and 14.5 MPa on the 3rd and the 90th day, respectively [63,66].

Table 8. Summary of reviewed studies for use of dredged material as a construction product.

Sources	Replacement	Supplementary Material	Optimum Result	Tests	Treatment	Outcome	References
Brazilian seaports (seaport of Paranagua in Parana State, Brazil)	Up to 60% replacement	Construction and demolition debris (20–35%), lime production wastes (15–30%)	15.4 MPa compressive strength (50% Dredged material, 20% construction and demolition waste, and 30% lime production waste)	XRD, XRF, SEM, EDS, AAS, and LAMMA analysis	-	Up to 60% can be used.	[41]

Table 8. *Cont.*

Sources	Replacement	Supplementary Material	Optimum Result	Tests	Treatment	Outcome	References
Coastal area in Hong Kong	80–95% replacement	Recycled fine aggregate, ordinary Portland cement, recycled glass, recycled coarse aggregate	Fill materials, partition blocks, and paving blocks use 5–10%, 20%, and 30% binder	TGA, XRD, ANOVA	-	Overall benefit for paving blocks (292 USD per m^3), fill material (236 USD per m^3), and partition blocks (117 USD per m^3).	[50]
Port of Antonina, Brazil	Overburden soil (40–60 wt%), dredging sludge sediments (20–40%), and lime production waste (15–30%).	Overburden soil, lime production waste	Blended material attained 11.4 MPa strength on the 28th day	XRD, XRF, AAS, SEM, EDS, DTA–DTG	Dried in a vacuum at 100 °C and milled	New composites can be made from three types of industrial waste material (overburdened clayey soil, dredged marine sludge, and lime production waste).	[48]
Harbor of Dunkirk, France	12.5% and 20%	Admixture	Limited to 12.5% of the concrete mix to prevent external sulfate attack and frost action	UPVT, frequency shift, CT, TT, ME, MIP, alkali-aggregate reaction, Sulfate test, Freeze-thaw reaction	Stored for 3 years duration before using	Less than 12.5% was declared non-economical; 20% was shown to be the maximum limit.	[14]
Urban waters, Arnhem, Netherlands	Cement (0–15%) and quicklime (0.5–1%)	Cement and quicklime	7% cement and 0.5% lime accelerate the ripening process 3 times and make DM a category 1 material ($\leq$3 m)	LT, XRD, XRF,	Ripening process	With the addition of binder, the total time for ripening is reduced by 70%; highly contaminated DM can be used as category 2 building material.	[46]

Dredged sediments find applications for the manufacture of a fly-ash-based geopolymer. The experimental results indicated that the use of dredged sediments can improve the mechanical properties of a geopolymer as compared to siliceous sand. Additionally, dredged sediment geopolymers containing specimens showed densely compacted microstructure but lower Young's modulus than the corresponding control specimen containing sand geopolymer [62].

Another study on DM from the Harbor of Napoli, Italy, prepared a geopolymer binding material by mixing 90% fly ash and 10% DM, which can be used as a binding material for construction work. It is important to note that the geopolymer material can reduce the emission of CO_2 by up to 80%, compared to cement. Hence, attention should be directed towards the use of DM as a geopolymer in future studies [49,62].

Several studies used DM for preparing non-sintered/sintered lightweight aggregates [5,49,51]. Peng prepared non-sintered waterproofing and wrap-shell lightweight aggregates made of dredged sediments. However, the untreated lightweight aggregates were found to have a low compressive strength of 0.27 MPa, but they did show a uniform particle size distribution and also had a water absorption of 24.18%. The wrap-shell lightweight aggregates were equipped with a tough and stable concrete shell, resulting in significantly higher compressive strength (2.46 MPa) than the untreated ones [58]. Using DM sediments and basic oxygen furnace slag to produce sintered lightweight aggregates at a preheating temperature of 500 °C for 10 min and sintering temperature of 1175 °C for 15 min. Laboratory testing results showed low water absorption and high compressive strength of 23.2 MPa when 27% when Basic Oxygen Furnace (BOF) slag was added [9]. In 2019, in order to develop new composites, use of dredged sludge (a muddy deposit on a riverbed) from marine port sediments (20–40% by weight) with overburden soil (40–60% by weight) and lime production waste as a binder (15–30% by weight) [63].

4.2.2. Green Infrastructure Material

Green infrastructure (GI) is defined as a cost-effective, resilient method to manage wet weather impacts that also brings community benefits. When compared with conventional piped drainage and water treatment systems, GI plays a significant role in reducing and treating stormwater at its source rather than merely moving urban stormwater away from the built environment. The use of dredged material for GI construction seems less common, but there are still several techniques proposed. Liu and Coffman [67] used DM from Lake Erie in Cleveland, Ohio, for green roof construction for stormwater management. The chemical and thermal analyses revealed that the sintered DM can be used for lightweight aggregate production when preheated at 550 °C and sintered at a higher temperature. The water absorption capacity of the aggregate was found to decrease as the sintering temperature increased. The lightweight aggregates sintered from DM were incorporated into the growing media of a green roof plot, which possessed a higher water retention capacity than a conventional green roof system [67]. Potential applications of the lightweight aggregates made using DM in bio-retention and vegetative roof systems were investigated [13]. Experimental results indicated that 100% replacement of traditional lightweight aggregates with DM-containing lightweight aggregates in Rooflite® growth media, a commercial standard product, produced acceptable performances of GI (Green Infrastructure) [13].

4.3. Roadway Construction

The literature review revealed that DM was used in roadway construction as a fill material for base or sub-base layers of pavement. Several studies stabilized DM sediments chemically using cementitious additives such as accelerators, retarders, dispersants, etc., and used it as a subgrade of the sub-base layer. Table 9 shows a summary of studies that used DM in roadway construction. Department of Transportation (DOT's) is likely the biggest potential user of DM. Further selected studies are discussed in subsequent sections.

Table 9. Summary of reviewed studies for use of dredged material in road construction.

Sources	Replacement /Addition	Supplementary Material	Optimum Result	Tests	Treatment	Outcome	References
Dunkirk Harbor in France	ROLAC®645 binder (6–8%)	Hydraulic binder ROLAC®645, fly ash	With an increase in binder content strength also increases	Modified Proctor compaction, UCS test, ME, CT, TT, I-CBR	Natural dewatering, sieving	Dredged material stabilized by a chemical binder can be used for subbase or base course material.	[66]
Harbor located in the South of France	Non-structural cemented mortar	Blast furnace slag, ordinary Portland cement	Processed sediments with 80 µm size, 80% replacement of slag with standard Portland cement	MIP, TGA/DSC tests, UCS test	Bioremediation, stored for 5 years in darkness at 4 °C, dried in a furnace at 45 °C	-	[62]
Eight French ports of the English channel	-	Quicklime, CEMII 32.5	3% of quicklime and 6% of cement CEMII 32.5	Standard Proctor test	Grinding (under 2 mm), dehydration in the oven at 40 °C, sediments crushing	Sediments are fine materials with high organic matter and clay activity.	[68]
South end of Milwaukee Harbor in Wiscon-sin	10, 20, and 30% FA and cured for 2 h, 7 days, and 28 days	Class C fly ash	30%	UCS, CBR, AL, FT, Resilient Modulus Tests, Unconsolidated Undrained Strength Tests	-	Stabilization with Class C fly ash can significantly improve the engineering properties of DM.	[69]
East Port of Dunkirk Harbor in France	0–30% binder	Cement, lime, Class-F fly ash.	Dredged soil mix with 9% cement	Water Immersion Ageing, FT, stress-strain curve, Swelling test	-	Class-F fly ash is incapable of improving the resistance to thawing-freezing and water immersion.	[67]

Table 9. *Cont.*

Sources	Replacement /Addition	Supplementary Material	Optimum Result	Tests	Treatment	Outcome	References
Dunkirk Harbor, North of France	-	20% and 80% phosphoric acid	Both acids gave the same results	Specific surface area, density test, WA, organic Matter test, AL, XRD, pH, I-CBR	Novosol® process, calcination	100% substitution after treatment.	[3]
Dunkirk Harbour, North of France	Replacing up to 60 fine sediment with dredged material	Cement and quicklime	Optimum result was obtained when adding both lime and cement	AL, CBR index, TT, ME, wetting and freezing cycles test, UCS, a Lime Fixation Point test	Decantation	Addition of lime with cement can change mechanical classification after 360 days.	[70]
Dunkirk marine dredged, France	6% OPC or blended cement with limestone and slag	Limestone, slag, lime	Max dry unit wt. 2.04 g/cm^3 Optimum water content is 11.6%	Modified Proctor tests, ME, TT	Dewatering, lime addition	Salinity of the sediments is equal to 31.4 g/L; 4.5% of organic matter.	[65]
Ansung, Jechon, and Mulwang Reservoirs in Korea.			Contents of heavy metals in dredged soil samples were lower than the environmental standards	XRD, XRF, heavy metal contamination, pH, electrical conductivity, wet sieve and hydrometer analysis, falling head permeability, CU triaxial compression tests	Air-dried in the laboratory at room temperature	pH value of the soil samples ranged from 4.25 to 5.39, and the electrical conductivity ranged between 83.3 and 265.0 mS/cm, indicating suitability for use as construction material with steel and concrete.	[37]
HuangBei Lake, China	Replace cement up to 100%.	Iron tailing slag, calcium carbide slag	When the ratio of DM, iron tailing slag, cement, and calcium carbide slag is 60:40:16:4	UCS, slump, AL, test, XRF, XRD		Calcium carbide slag elevates the flowability. Solve the problem of subsidence. Calcium carbide slag is similar to hydraulic lime.	[44]
Mouth of Neches River, Texas	Lime mixed at 4, 6, 8, 10, and 12% of dry weight of DM. Other additives (PC and FA) were mixed at 1.5, 3.0, 4.5, 6.0, and 7.5% of DM.	Quicklime, Hydrated lime, Portland cement, Class F fly ash	DM with 6% Portland Cement	UCS, ANOVA, chemical analysis		Cost-effective and environmentally friendly and reduces the overall use of cement products.	[49]
Peoria Lakes Illinois River, USA	20–100% replacement	Compost, Bio-solid, horse manure	50% sediment and 50% bio-solid for Barley; 70% sediment and 30% bio-solid for Snapbean.	Water holding capacity, soil texture, pH, salt content, metal content	Sieving DM with a 10 mm sieve	Barley crops gave a good yield compared to snap beans.	[71]
Izmir Bay, Turkey	5–20% mixing of each material (Lime, fly ash, and volcanic slag) separately in 4 types of dredged soil	Lime, Fly ash, and volcanic slag	Thermal power plant fly ash is the most effective additive	SEM, XRD, FTIR, AL, pH, specific gravity		Mixed dredged samples have better geotechnical properties and lower compression indexes than natural samples, except for volcanic slag.	[72]
South Baltic Sea	Replace 100% stabilized natural soil	Geo-synthetic grid,			1 year of dewatering	Hydraulic conductivity of about 5×10^{-6} m/s; turbulent and supercritical flow conditions showed a medium erosion resistance.	[73]

4.3.1. Fill Material

A series of studies were conducted to investigate the beneficial reuse of DM as fill material in road construction [44,68,72–74]. In a laboratory study, DM sediments can be reused in a sub-base for road construction when the water content of DM is less than 20% [68]. In another study, three different types of mixtures consisting of dewatered sediments, dredged sand, Boulogne sand, and Portland/blended cement were used to examine the usability of DM in foundations and base layers of pavement, satisfying the European Standard of bearing capacity (European Standard, NF EN 13286-47, 2003) [44]. The research results indicated that a mixture of 27% dewatered sediment, 37% dredged sand, 28% Boulogne sand, and 8% Portland cement as the binder can be used as fill material in both the foundation and base layers of pavement. Using a decrement of 2% Portland cement and an increment of 2% dredged sand without changing the other two components, the new mix was still applicable for the foundation and base layers of pavement. In another study, a similar technique discarded the use of Boulogne sand [72]. Specifically, a mixture containing 32.4% dewatered sediment, 60.2% dredged sand, and 5.6% cement was found suitable as a fill material for the pavement base layer.

4.3.2. Stabilized Soil Subgrade

As discussed earlier, a few studies used DM as a pavement subgrade material in roadway construction by stabilizing it with cementitious additives such as Class C fly ash and cement and lime [70,75,76]. Naturally dried and sieved DM mixed with 6–8% ROLAC®645 hydraulic binder improved the compressive strength 7.5 times and the tensile strength 11.75 times when compared to the corresponding strength of a control mixture (normal concrete mix without any replacement of its ingredients) without DM. Improvement in strength was attributed to the formation of Calcium-Silicate Hydrate (C-S-H) gel, which possessed cementitious properties [70]. DM can be used to replace 100% sand to construct a pavement base in addition to 80% cement replacement with slag. The result showed that replacing 80% cement with slag in a stabilized base mixture provided acceptable strength. Also, with a coarser fraction of DM (>80 μm), improvement in compressive strength values was observed [49]. DM containing water content of up to 200% and high organic material as a sub-base material for pavement construction after stabilizing it with 3% quicklime and 6% cement [77].

The engineering property and durability of DM increased after the addition of class C fly ash. However, acceptable strength values were observed when the percentage of fly ash was greater than 20% [75]. The swelling and durability behavior of DM after the addition of cement, lime, and Class F fly ash was found to be a reduction in swelling potential. All the different mixtures proposed in the study are acceptable to use as a foundation material for road construction, as all mixtures showed swelling potential within a permissible limit of 5%. However, the addition of Class F fly ash was not able to improve the freezing/thawing and water immersion resistance. Cement was a better additive when compared to lime and fly ash for improving compressive strength [70]. Phosphoric acid (H_3PO_4) was used to treat heavy metals by converting them into metal phosphate, followed by calcination at 650°C to remove organic content. Phosphatation also reduced water content from 135% to 5%, which reduced the cost of transportation and helped in the valorization of DM. Further, different concentrations of phosphoric acid gave approximately the same results [3].

DM with iron tailing slag, calcium carbide slag, and cement for backfilling material provided a compressive strength of 2.9 MPa after seven days of curing. The addition of Portland cement decreased the slump, but iron tailing slag improved slump values (more slump value means more workability). It was also observed that up to 20% of the cement replaced by calcium carbide slag improved the strength. The concrete slump test measures the consistency of fresh concrete before it sets. It is performed to check the workability of freshly made concrete and the ease with which concrete flows [78]. Compressive strength results after adding Class F fly ash, quicklime, hydraulic lime, and cement into the DM. Adding 7.5% fly ash and 6% hydraulic lime increased strength by 2.25 and 2.77 times, respectively, while the addition of 6% cement enhanced the strength by 3.45 times. The addition of a small amount of lime (4%) or Class-F fly ash (4.5%) was found to change the group of DM soil from CH fat clay to MH in accordance with the Unified Soil Classification System [76]. DM can be stabilized using lime, volcanic slag, and fly ash. The compressive strength of DM decreased by adding lime and fly ash, but volcanic slag showed the opposite behavior. Hence, volcanic slag was not recommended to improve the geotechnical properties of DM. Further from economic considerations, fly ash should be used as a stabilizer [79].

4.4. Habitat Building

Dredged material can be used to create, restore, or maintain wetland, upland, island, and aquatic areas to support species that are displaced or even endangered due to the destruction of habitats [2,6]. Depending on its composition, DM can be utilized in the following projects: the creation of shoals, spits, and bars, oyster reef restoration, bathymetric recontouring, creation/restoration of intertidal marshes and mudflats, filling of bird/wildlife islands, and remediation/creation of upland habitats [80]. Artificial shoals are usually defined as underwater berms, including a feeder berm that places sand to erode and provide stable refuge and feeding habitats for juvenile and adult life stages of a variety of finfish and crustaceans [81].

Several key factors associated with the construction of underwater berms using DM, including height and shape, the grain size distribution of sediments, the effects of the berm on local hydrodynamics, and the development of the benthic and epi-benthic prey resources in the vicinity of the berm should be considered before construction. However, due to the uncertainty of whether sediment berms will provide a habitat value in addition to shore protection, field studies are needed to document the fishery habitat values of existing sedimentary bars and mounds [80].

Building new islands or enlarging existing ones is a likely utilization of DM from backwaters and side channels [82]. Constructed islands may need to be long and narrow to minimize the impacts on flood heights in rivers. They can also be built high enough to provide habitats for floodplain hardwood trees and other native species that are unable to adapt to the current altered hydrologic conditions. Constructed islands also block wind fetch and wave action to promote aquatic habitat, and they provide safe nesting and resting areas for birds.

Looking at the State of Illinois and its unique topographical characteristics [43], the most feasible habitat project involving the use of DM would be wetland creation/restoration. In pursuing the validity of wetland projects using dredged materials in Illinois, the notes taken through the personal interview with Suzanne Wagner, Director of Development and Communications for the Wetland Initiative in Illinois, indicated that her organization does not perceive a use for these materials at this time. Often, the Wetland Initiative engages in projects involved with the removal of materials from wetland spaces as opposed to their addition. Additionally, Wagner expressed concerns over the dredged material being sediment that sits idle for long periods at the bottom of a waterway, insisting that healthy wetlands require hydric soil. According to the USDA, soil that is hydric in nature is "soil formed under conditions of saturation, flooding, or ponding long enough during the growing season to develop anaerobic conditions in the upper part" [71]. While the Nature Conservancy has been a stakeholder/advisor to the US Army Corps of Engineers on some of its projects, Jeff Walk, the Illinois Director of Conservation for the Nature Conservancy, provided some insight on his organization's trepidation towards dredged materials. This organization does not feel prepared to use dredged material itself due to its limited material needs. Meanwhile, the Nature Conservancy participates in floodplain restoration and reconnection projects on Midwest rivers, using biological materials such as seed and fish stock, as well as some construction materials. However, currently, as an alternative, DM is not needed or used to restore or reconnect floodplains on Midwest rivers. Through the interviews, it is apparent that governmental organizations involved in habitat creation have been aware of the existence of dredged materials. However, the current challenge is that decision-makers do not see the potential use of DM in their own projects. Moreover, the typical nationwide process may be implemented differently by different states. Some are more rigorous, while some may be more lenient. This could potentially be overcome by educating these organizations on the exact composition of the material and real-world projects in which it has been successfully utilized in the past. As evidenced by the Nature

Conservancy's collaboration with the Army Corps of Engineers, the interest and awareness are present, but the confidence is not.

4.5. Landfill Liner or Cap

A landfill liner is an impermeable membrane at the bottom of the landfill that prevents its contents from leaching into the ground and local water sources [80]. Likewise, a landfill cap is a material placed on top of a landfill to prevent contaminants from reaching wildlife and the public via wind, precipitation runoff, gas release, and the like [83]. Based on a study conducted by the San Francisco Bay Conservation and Development Commission (BCDC), only DM from the Bay are generally suitable at landfills (once dried) for being utilized as cover, on-site construction, capping, or lining material. A cap design that comprised of topsoil of 1 ft. (0.31 m) sandy DM layer underlain by a 2 ft. (0.61 m) low permeability clayey DM layer was proposed and proved as a cost-effective barrier for the closure of a solid waste landfill [84,85].

According to the USACE, it was found that DM with a classification of lean clay (CL) or fat clay (CH) is likely to be applicable for use in constructing a liner or barrier that serves the purpose of preventing the migration of leachate water or decomposition gases in landfills. It was also recommended to keep these liners or barriers saturated with water to prevent cracking and retain gases. At least a 6 in. (15 cm) thick dewatered DM cover for the closure of a solid waste sanitary landfill was recommended to prevent internal fires and control surface water infiltration [6].

4.6. Agriculture: Soil Reconstruction/Remediation

In agriculture, DM has been a valuable ingredient for manufacturing soil products that provide farmers with soil for reconstruction and/or remediation. For example, soil made using municipal tree waste, dredged material, manure, backwater sediment, and agricultural by-products was proposed to reduce the operational costs for the disposal of DM and enlarge the economic benefits of DM simultaneously [6]. Dredged materials obtained from Woodrow Wilson Bridge, Maryland, and Earle Naval Weapons Station, New Jersey, have been utilized as agricultural soil media [83]. In addition, using DM from Illinois Rivers as high-value agricultural or horticultural soils has been notably recorded in various studies [17,86–89]. Lee et al. [20] stated that DM obtained from the mid-Atlantic coast can be used to create soils for a wide range of applications, such as brownfield redevelopment, gardening, and landscaping. Especially, DM from freshwater bodies should be actively considered as topsoil in urban areas due to its no adverse effects on the local environment [83]. However, due to the presence of heavy metals and phosphorus in most of DM and its potential contamination to groundwater, there is a need to address these concerns prior to the beneficial use of DM for soil reconstruction/remediation.

4.7. Beach Nourishment

Beach nourishment is one of the most desirable and cost-effective measures to deal with shoreline erosion in the Great Lakes and coasts [6]. Current activities of beach nourishment for U.S. shorelines can be categorized into four main types, including borrow dredging, maintenance, and new-work dredging, dumping in the littoral zone, and re-handling stockpiled material [6]. For example, borrow dredging is usually implemented by dredging sand from inshore or offshore sites and then transporting the dredged sand by truck, split-hull hopper dredge, or hydraulic pipeline to an eroding beach. Using the Great Lakes as an example, beach nourishment was conducted using berms to decrease shore erosion caused by water waves and to supplement sand to the eroding beaches [2].

4.8. Other Beneficial Uses

4.8.1. Embankment Fill

Various blends mixed with crushed glass and dredged material were prepared and evaluated in the field to explore their feasibility of use in general, embankment, and structural fill applications. The addition of crushed glass showed improvement in the geotechnical properties of the DM and provided realistic opportunities for the large-scale beneficial utilization of both glass and DM in the urban environment [34]. DM was also blended with steel slag fines as synthetic fill materials via a combined laboratory and field demonstration project. The DM-slag blends had comparable and superior strengths to other conventional soils used for embankment construction [35,46]. DM obtained from reservoirs in South Korea for potential reuse as embankment fill material was sufficient for substitution of existing embankment and core material and even applicable as new embankment material for expansion, i.e., increasing the width/length of embankment [55].

4.8.2. For Making Cement

Only a few studies reported the beneficial use of DM as a raw material for cement production, as shown in Table 10. DM is applicable in producing cement or lightweight aggregates and manufacturing glass tiles [50]. Among these, all producing/manufacturing techniques were involved with high-temperature treatment and thus were energy-intensive and costly [2]. Innovatively, dredged fluvial sediments were utilized as a novel supply of raw material to make Portland cement clinker; Portland cement clinker is very finely ground to produce Portland (hydraulic) cement [90]. The results indicated that Portland cement clinker can be synthesized by using up to 39% sediment. The compressive strengths developed by the cement are equal to those obtained with regular Portland cement at early stages (less than 14 days), even 20% higher in the long term (56 days). However, since the production of cement is not only reliant on raw materials but also strongly dependent on energy consumption, no relevant economic analysis of using DM as a raw material to produce cement was found in the literature. Therefore, it is not clear if the beneficial reuse of DM as raw material for cement production is economically acceptable for full-sale applications.

Table 10. Summary of reviewed studies for use of dredged material as a cement substitute.

Sources	Types of Cement Replaced	Replacement Description	Supplementary Material	Optimum Result	Treatment	Outcome	References
Northern coast of Brittany, France	-	8%, 16% and 33% of CEM I (52.5)	Limestone	8% replacement with heating at 650 °C	Treated at high-temperatures (650 °C and 850 °C) to eliminate all organic compounds and activate the clay minerals; washing to remove chloride content	Hydration process required more time to complete; apparent porosity increased; at 33%, blended cement permeability decreased; strength decreased but within limits.	[52]
Ulu Pandan, Singapore.	Ordinary Portland cement	30% cement replacement by marine clay or quartz	Quartz; CEM I (52.5)	30% calcined dredged material at 700 °C	Drying for 72 h, ball mill grinding, calcination at namely 600 °C, 700 °C and 800 °C	Strength is reduced when replaced with dredged marine clay.	[58]
Port of Oran, Mediterranean Sea	Cement in mortar	DM replaces cement (5%,10%,15% and 20%)	3% phosphoric acid by mass	5% replacement (strength decreases as the DM increases)	Chemical treatments, leaching, dewatering, sieving ($\Phi \leq 80$ μ)	Polluted by both heavy metals and hydrocarbons; DS can be substituted partially for the cement used in the manufacture of cement.	[42]

Table 10. *Cont.*

Sources	Types of Cement Replaced	Replacement Description	Supplementary Material	Optimum Result	Treatment	Outcome	References
Ruzin Reservoir in Slovakia	Portland cement	40% sediment replaces cement with and without granulated NaOH milled for 3 min	Granulated NaOH	20% and 40% lower compressive strength after 28 and 90 days, respectively.	Dry milling, milling with granulated NaOH	Strength of cement is reduced by adding dredged sediment.	[47]
Harbor of Napoli (South of Italy)	Fly ash		Fly ash, HNO_3, HCl, HF, H_3BO_3	10% fly ash replaced by dredged material	Calcination at 550 °C for two hours	Reducing emissions by 80% compared to Portland cement.	[39]

5. Discussion and Conclusions

This study summarized the technical innovations or expansion of the application scale of DM utilization via a survey of the literature. Overall, the review indicates there are many varied uses for DM, and the physical and chemical properties such as moisture content, grain distribution, and chemical composition must be characterized to evaluate DM uses. The definition of DM and its sources and types were also determined in this study. The innovative techniques in current practice were summarized for a wide range of domains, including as a substitute for sand and cement in concrete materials, as a composite material and green infrastructure material for construction products, and as fill material and stabilized soil subgrade for roadway construction. Further, the use of DM in habitat building, landfill liner/cap, agriculture soil reconstruction, and beach nourishment was also discussed.

5.1. Beneficial Use of Dredged Material

Based on the literature discussed in this paper, the following conclusions could be drawn about beneficial use of dredged material:

- DM is composed of sorted solid particles, namely sand, silt, and clay derived from the watershed. It may contain heavy metals (e.g., mercury, cadmium, arsenic) and organics (e.g., benzene, naphthalene, dioxins);
- Based on the levels of heavy metals and toxic substances, DM can be categorized into three management levels, namely: Level 1—use, reuse for residential and recreational purposes; Level 2—use, reuse for industrial purposes; and Level 3—significant contamination with no use and reuse;
- Depending on the gradation and contamination level, DM can replace sand up to 50% with treatment and 100% after treatment in concrete materials. Specifically, if chloride content is less than 0.18% or the total chloride content in concrete is less than 0.34%, then it is safe in concrete against reinforcement corrosion;
- Contaminated DM could be treated by washing, grinding, and calcination to obtain the permissible limit of heavy metals. Washing the DM reduces free chloride content by up to 80%. Calcination is the heating of DM to a high temperature for the purpose of removing volatile substances. Calcination after grinding helps with the activation of clay minerals;
- Treated DM could be used as a partial cement substitute in concrete materials. However, it is not clear if the beneficial reuse of DM as raw material for cement production is economically acceptable for real practices;
- DM could be used for making products such as tiles, bricks, and blocks, but the cost associated with each product was not available in the literature;
- DM with less than 20% water content can be used as fill material in both the foundation and base layer of pavements;
- For pavement applications, DM could be used as subgrade after treating with class C fly ash;
- DM is suitable for many agricultural applications;

- Another application of DM is habitat building, landfill liner or cap, and beach nourishment.

5.2. Practical Challenges/Limitations in Using and Managing Dredged Material

Throughout a comprehensive investigation of the beneficial uses of DM, three main challenges/limitations in using and managing DM were identified in this study. First, users/customers have a low willingness to introduce new materials partially or fully made of DM to their current operations due to their inadequate awareness of DM itself and its beneficial uses. Second, it is challenging to put DM products into the market due to a lack of consistent policy documenting the safety of DM. Third, the cost to transport DM for beneficial use was also noticed as the greatest practical barrier to beneficial uses.

5.3. Tips/Resources to Help Communities Become Involved with Beneficial Use

The success of any beneficial use program may rely on local communities since they play a significant role in identifying the projects that might be suitable for reusing DM instead of source material. Therefore, it is critical to have public engagement with DM beneficial reutilizing. Tips/resources shown below can be taken into consideration by scientists, engineers, decision-makers, contractors, and other stakeholders to maximize public awareness and involvement:

- Form a committee, task force, or subgroup within existing local government agencies such as the Farm Bureau or Environmental Protection Agency at a state administration level. For instance, the Illinois Farm Bureau can invite farmers, port authorities, economic development groups, institutional researchers or scientists, college students, etc., from different areas in the state to participate in the discussion and proposal-making in terms of using DM along with other wastes to custom more productive soils for farming;
- Develop a web-based tool like a website to provide the public with the most accessible and up-to-date information about the beneficial reuse of DM and potential risks affiliated with it, the frequently asked questions and corresponding answers, and a map finder that gives specific location information about the sediments nearby. The Natural Infrastructure Opportunities Tool (NIOT) is one example that helps match available resources for natural infrastructure projects by compiling placement area capacities, dredging plans, and sediment characteristic descriptions and help to identify beneficial use and infrastructure opportunities;
- Organize a seminar series at nearby higher education institutions or professional organizations to systematically educate the public about the economic benefits of using DM.

5.4. Next Steps

As a result of this preliminary research, the first step in marketing the DM to the public is to establish a clear image of what the material's properties are. Based on survey trends, knowing the chemical benefits and drawbacks based on organic matter, nutrient content, pH, and trace elements are baseline details that will lead to a more definite determiner of market interest. In outlining these details, establishing a social media campaign to create public awareness is something that appears to be needed, as those who are interested in the material seem to need an extra push to follow through with what they already know about the material's existence. For those who are uninterested, public exposure of the material's benefits, both in practice and practicality, would call to light why the alternative is essential in their operations. The high abundance and low cost of the material should be enough to establish a change in market interest, but there needs to be more clarity on the costs and risks to appease current economic apprehensions. Pairing these actions with the current interest in university-based research would increase salience in the usability of the material and build a foundation for public benefit. Ultimately, with increased attention, engineered soil would become more desirable across all markets and offset the growth of stockpiled dredged material.

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Abbreviations

Al_2O_3	Alumina
As	Arsenic
BCDC	Bay Conservation and Development Commission
BOF	Basic Oxygen Furnace
CaO	Calcium Oxide
CDFs	Confined Disposal Facilities
Cr	Chromium
C-S-H	Calcium-Silicate-Hydrate
Cu	Copper
CWA	Clean Water Act
CZMA	Coastal Zone Management Act
DM	Dredged Materials
DOT	Department of Transportation
Fe_2O_3	Iron Oxide
GI	Green Infrastructure
H_3PO_4	Phosphoric Acid
MPCA	Minnesota Pollution Control Agency
Ni	Nickel
Pb	Lead
RCRA	Resource Conservation and Recovery Act
SiO_2	Silica
SRV	Soil Reference Value
TSCA	Toxic Substances Control Act
USACE	United States Army Corps of Engineers
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey
Zn	Zinc

References

1. Sheehan, C.; Harrington, J.J.W.M. Management of dredge material in the Republic of Ireland—A review. *Waste Manag.* **2012**, *32*, 1031–1044. [CrossRef]
2. USEPA; USACE. *Identifying, Planning, Financing Beneficial Use Projects Using Dredged Material: Beneficial Use Planning Manual*; Defense Technical Information Center: Fort Belvoir, VA, USA, 2007; p. 115.
3. Dia, M.; Ramaroson, J.; Nzihou, A.; Zentar, R.; Abriak, N.E.; Depelsenaire, G.; Germeau, A. Effect of Chemical and Thermal Treatment on the Geotechnical Properties of Dredged Sediment. *Procedia Eng.* **2014**, *83*, 159–169. [CrossRef]
4. Costa-Pierce, B.A.; Weinstein, M.P. Use of dredge materials for coastal restoration. *Ecol. Eng.* **2002**, *19*, 181–186. [CrossRef]

5. Limeira, J.; Etxeberria, M.; Agulló, L.; Molina, D. Mechanical and durability properties of concrete made with dredged marine sand. *Constr. Build. Mater.* **2011**, *25*, 4165–4174. [CrossRef]
6. United States Army Corps of Engineers. *Dredging and Dredged Material Management*; United States Environmental Protection Agency: Washington, DC, USA, 2015; p. 920. Available online: http://www.publications.usace.army.mil/Portals/76/Publications/EngineerManuals/EM_1110-2-5025.pdf (accessed on 30 May 2023).
7. U.S. Army Corps of Engineers (USACE). Inner Harbor Navigation Canal Lock. 2017. Available online: https://www.mvn.usace.army.mil/Portals/56/docs/Projects/IHNC/IHNC%20Lock%20Study-%20Eng%20Appendix%20B%20.pdf?ver=2016-12-30-131854-877 (accessed on 29 November 2020).
8. Mostafa, Y.E.S. Environmental impacts of dredging and land reclamation at Abu Qir Bay, Egypt. *Ain Shams Eng. J.* **2012**, *3*, 1–15. [CrossRef]
9. Lim, Y.C.; Lin, S.K.; Ju, Y.R.; Wu, C.H.; Lin, Y.L.; Chen, C.W.; Di Dong, C. Reutilization of dredged harbor sediment and steel slag by sintering as lightweight aggregate. *Process. Saf. Environ. Prot.* **2019**, *126*, 287–296. [CrossRef]
10. Bolam, S.G.; Rees, H.L.; Somerfield, P.; Smith, R.; Clarke, K.R.; Warwick, R.M.; Atkins, M.; Garnacho, E. Ecological consequences of dredged material disposal in the marine environment: A holistic assessment of activities around the England and Wales coastline. *Mar. Pollut. Bull.* **2006**, *52*, 415–426. [CrossRef] [PubMed]
11. Cesar, A.; Lia, L.R.B.; Pereira, C.D.S.; Santos, A.R.; Cortez, F.S.; Choueri, R.B.; De Orte, M.R.; Rachid, B.R.F. Environmental assessment of dredged sediment in the major Latin American seaport (Santos, São Paulo—Brazil): An integrated approach. *Sci. Total Environ.* **2014**, *497–498*, 679–687. [CrossRef]
12. Clark, G.R.; Knight, D.L.; Commission, G.L.; Clark, G.R. *Summit on the Beneficial Use of Dredged Materials: Turning a Surplus Material into a Commodity of Value*; U.S. Department of Transportation: Washington, DC, USA, 2014. Available online: https://rosap.ntl.bts.gov/view/dot/27782 (accessed on 30 May 2023).
13. Bhairappanavar, S.; Liu, R.; Coffman, R. Beneficial Uses of Dredged Material in Green Infrastructure and Living Architecture to Improve Resilience of Lake Erie. *Infrastructures* **2018**, *3*, 42. [CrossRef]
14. Amar, M.; Benzerzour, M.; Kleib, J.; Abriak, N.E. From dredged sediment to supplementary cementitious material: Characterization, treatment, and reuse. *Int. J. Sediment Res.* **2021**, *36*, 92–109. [CrossRef]
15. United States Environmental Protection Agency (USEPA). *Handbook—Remediation of Contaminated Sediments*; United States Environmental Protection Agency: Washington, DC, USA, 1991.
16. Agostini, F.; Skoczylas, F.; Lafhaj, Z. About a possible valorisation in cementitious materials of polluted sediments after treatment. *Cem. Concr. Compos.* **2007**, *29*, 270–278. [CrossRef]
17. Ebbs, S.; Talbott, J.; Sankaran, R. Cultivation of garden vegetables in Peoria Pool sediments from the Illinois River: A case study in trace element accumulation and dietary exposures. *Environ. Int.* **2006**, *32*, 766–774. [CrossRef]
18. Oudejans, L. *Report on the 2016 U.S. Environmental Protection Agency (EPA) International Decontamination Research and Development Conference*; U.S. Environmental Protection Agency: Washington, DC, USA, 2017.
19. Minnesota Pollution Control Agency Report. 2015. Available online: https://www.pca.state.mn.us/sites/default/files/lrw-sw-1sy15.pdf (accessed on 30 May 2023).
20. Lee, C.R.; Brandon, D.L.; Price, R.A. *Manufactured Soil Field Demonstration for Constructing Wetlands to Treat Acid Mine Drainage on Abandoned Minelands*; U.S. Army Corps of Engineers: Washington, DC, USA, 2007. Available online: https://apps.dtic.mil/sti/pdfs/ADA474492.pdf (accessed on 30 November 2020).
21. Ghiorso, M. Magmatic Process Modeling. In *Encyclopedia of Geochemistry*; Springer: Berlin/Heidelberg, Germany, 2018. [CrossRef]
22. Seibold, E.; Berger, W. *The Sea Floor*; Springer International Publishing: Cham, Switzerland, 2017. [CrossRef]
23. White, W.M. *Encyclopedia of Geochemistry*; Springer International Publishing: Berlin/Heidelberg, Germany, 2018. Available online: https://www.springer.com/gp/book/9783319393117 (accessed on 12 June 2021).
24. Gallmetzer, I.; Haselmair, A.; Stachowitsch, M.; Zuschin, M. An innovative piston corer for large-volume sediment samples. *Limnol. Oceanogr. Methods* **2016**, *14*, 698–717. [CrossRef]
25. Augustyn, A.; Chopra, S.; Curley, R.; Jain, P.; Lotha, G.; Cunningham, J.M.; Manchanda, K.; Rafferty, J.P.; Pallardy, R.; Sampaolo, M.; et al. Sedimentary Rock, (n.d.). Available online: https://www.britannica.com/science/sedimentary-rock (accessed on 12 June 2021).
26. Krause, P.R.; Mcdonnell, K.A. *The Beneficial Reuse of Dredged Material for Upland Disposal*; Harding Lawson Associates: Novato, CA, USA, 2000.
27. Ramirez, A.; Kot, C.; Piatkowski, D. *Review of Sea Turtle Entrainment Risk by Trailing Suction Hopper Dredges in the US Atlantic and Gulf of Mexico and the Development of the ASTER Decision Support Tool*; US Department of the Interior, Bureau of Ocean Energy Management: Washington, DC, USA, 2017; p. 266. Available online: https://espis.boem.gov/final%20reports/5652.pdf (accessed on 30 May 2023).
28. USEPA. Evaluating Environmental Effects of Dredged Material Management Alternatives—A Technical Framework. 2004. Available online: https://www.epa.gov/sites/production/files/2015-09/documents/2004_08_20_oceans_regulatory_dumpdredged_framework_techframework.pdf (accessed on 30 May 2023).
29. Hails, J.R. Grab samplers. In *Beaches and Coastal Geology*, 1986th ed.; Kluwer Academic Publishers: Dordrecht, The Netherlands, 2006; pp. 454–455. [CrossRef]

30. Folk, R.L. *Petrology of Sedimentary Rocks*; Austin Hemphill Publishing Company: Austin, TX, USA, 1974; p. 182.
31. Naqvi, S.M.; Pullen, E.J. *Effects of Beach Nourishment and Borrowing on Marine Organisms*; National Technical Information Service, Operations Division: Fort Belvoir, VA, USA, 1982. [CrossRef]
32. Wentworth, C.K. A Scale of Grade and Class Terms for Clastic Sediments. *J. Geol.* **1922**, *30*, 377–392. [CrossRef]
33. Shepard, F.P. Nomenclature Based on Sand-silt-clay Ratios. *J. Sediment. Res.* **1954**, *24*, 151–158. [CrossRef]
34. Grubb, D.G.; Davis, A.F.; Sands, S.C.; Carnivale, M.; Wartman, J.; Gallagher, P.M. Field Evaluation of Crushed Glass–Dredged Material Blends. *J. Geotech. Geoenviron. Eng.* **2006**, *132*, 577–590. [CrossRef]
35. Malasavage, N.E.; Jagupilla, S.; Grubb, D.G.; Wazne, M.; Coon, W.P. Geotechnical Performance of Dredged Material—Steel Slag Fines Blends: Laboratory and Field Evaluation. *J. Geotech. Geoenviron. Eng.* **2012**, *138*, 981–991. [CrossRef]
36. Folk, L. The Distinction between Grain Size and Mineral Composition in Sedimentary-Rock Nomenclature. *J. Geol.* **1954**, *62*, 344–359. Available online: https://www.jstor.org/stable/30065016 (accessed on 30 May 2023). [CrossRef]
37. Schlee, J. *Atlantic Continental Shelf and Slope of the United States—Sediment Texture of the Northeastern Part*; United States Geological Survey: Reston, VA, USA, 1973. [CrossRef]
38. Poppe, L.J.; Williams, S.J.; Paskevich, V.F. *USGS East-Coast Sediment Analysis. Procedures, Database, and GIS Data: U.S. Geological Survey Open-File Report 2005-1001*; United States Geological Survey: Reston, VA, USA, 2005.
39. Ramaroson, J.; Dirion, J.L.; Nzihou, A.; Depelsenaire, G. Characterization and kinetics of surface area reduction during the calcination of dredged sediments. *Powder Technol.* **2009**, *190*, 59–64. [CrossRef]
40. Medeiros, M.H.F.; Gobbi, A.; Réus, G.C.; Helene, P. Reinforced concrete in marine environment: Effect of wetting and drying cycles, height and positioning in relation to the sea shore. *Constr. Build. Mater.* **2013**, *44*, 452–457. [CrossRef]
41. Aoual-Benslafa, F.K.; Kerdal, D.; Ameur, M.; Mekerta, B.; Semcha, A. Durability of Mortars Made with Dredged Sediments. *Procedia Eng.* **2015**, *118*, 240–250. [CrossRef]
42. Wang, H.Y. Durability of self-consolidating lightweight aggregate concrete using dredged silt. *Constr. Build. Mater.* **2009**, *23*, 2332–2337. [CrossRef]
43. United States Geological Survey (USGS). Aggregates Data by State, Type, and End Use; 1971–2016, (n.d.). Available online: https://www.usgs.gov/atom/99519 (accessed on 29 November 2020).
44. Siham, K.; Fabrice, B.; Edine, A.N.; Patrick, D. Marine dredged sediments as new materials resource for road construction. *Waste Manag.* **2008**, *28*, 919–928. [CrossRef]
45. Illinois Environmental Protection Agency. *Tiered Approach to Corrective Action Objectives*; Illinois Environmental Protection Agency: Springfield, IL, USA, 1997.
46. Clare, K.E.; Sherwood, P.T. The effect of organic matter on the setting of soil-cement mixtures. *J. Appl. Chem.* **1954**, *4*, 625–630. [CrossRef]
47. Zhu, N.; Jin, F.; Kong, X.; Xu, Y.; Zhou, J.; Wang, B.; Wu, H. Interface and anti-corrosion properties of sea-sand concrete with fumed silica. *Constr. Build. Mater.* **2018**, *188*, 1085–1091. [CrossRef]
48. Dang, T.A.; Kamali-Bernard, S.; Prince, W.A. Design of new blended cement based on marine dredged sediment. *Constr. Build. Mater.* **2013**, *41*, 602–611. [CrossRef]
49. Couvidat, J.; Benzaazoua, M.; Chatain, V.; Bouamrane, A.; Bouzahzah, H. Feasibility of the reuse of total and processed contaminated marine sediments as fine aggregates in cemented mortars. *Constr. Build. Mater.* **2016**, *112*, 892–902. [CrossRef]
50. Millrath, K.; Kozlova, S.; Meyer, C.; Shimanovich, S. *Beneficial Use of Dredge Material, Progress Report*; Columbia University: New York, NY, USA, 2001.
51. Ozer-Erdogan, P.; Basar, H.M.; Erden, I.; Tolun, L. Beneficial use of marine dredged materials as a fine aggregate in ready-mixed concrete: Turkey example. *Constr. Build. Mater.* **2016**, *124*, 690–704. [CrossRef]
52. Liu, W.; Huang, R.; Fu, J.; Tang, W.; Dong, Z.; Cui, H. Discussion and experiments on the limits of chloride, sulphate and shell content in marine fine aggregates for concrete. *Constr. Build. Mater.* **2018**, *159*, 725–733. [CrossRef]
53. Wang, L.; Chen, L.; Tsang, D.C.W.; Li, J.S.; Baek, K.; Hou, D.; Ding, S.; Poon, C.S. Recycling dredged sediment into fill materials, partition blocks, and paving blocks: Technical and economic assessment. *J. Clean. Prod.* **2018**, *199*, 69–76. [CrossRef]
54. Stollenwerk, J.; Smith, J.; Ballavance, B.; Rantala, J.; Thompson, D.; McDonald, S.; Schnick, E. *Managing Dredged Materials*; Minnesota Pollution Control Agency: Baxter, MN, USA, 2014. Available online: https://www.pca.state.mn.us/sites/default/files/wq-gen2-01.pdf (accessed on 30 May 2023).
55. Park, J.; Son, Y.; Noh, S.; Bong, T. The suitability evaluation of dredged soil from reservoirs as embankment material. *J. Environ. Manag.* **2016**, *183*, 443–452. [CrossRef] [PubMed]
56. Yan, M.; Sun, C.; Xu, J.; Dong, J.; Ke, W. Role of Fe oxides in corrosion of pipeline steel in a red clay soil. *Corros. Sci.* **2013**, *80*, 309–317. [CrossRef]
57. Achour, R.; Zentar, R.; Abriak, N.E.; Rivard, P.; Gregoire, P. Durability study of concrete incorporating dredged sediments. *Case Stud. Constr. Mater.* **2019**, *11*, e00244. [CrossRef]
58. Peng, X.; Zhou, Y.; Jia, R.; Wang, W.; Wu, Y. Preparation of non-sintered lightweight aggregates from dredged sediments and modification of their properties. *Constr. Build. Mater.* **2017**, *132*, 9–20. [CrossRef]
59. Brouwers, H.J.H.; Augustijn, D.C.M.; Krikke, B.; Honders, A. Use of cement and quicklime to accelerate ripening and immobilize contaminated dredging sludge. *J. Hazard. Mater.* **2007**, *145*, 8–16. [CrossRef] [PubMed]

60. Junakova, N.; Junak, J. Recycling of Reservoir Sediment Material as a Binder in Concrete. *Procedia Eng.* **2017**, *180*, 1292–1297. [CrossRef]
61. Du, H.; Pang, S.D. Value-added utilization of marine clay as cement replacement for sustainable concrete production. *J. Clean. Prod.* **2018**, *198*, 867–873. [CrossRef]
62. Lirer, S.; Liguori, B.; Capasso, I.; Flora, A.; Caputo, D. Mechanical and chemical properties of composite materials made of dredged sediments in a fly-ash based geopolymer. *J. Environ. Manag.* **2017**, *191*, 1–7. [CrossRef]
63. Mymrin, V.; Stella, J.C.; Scremim, C.B.; Pan, R.C.Y.; Sanches, F.G.; Alekseev, K.; Pedroso, D.E.; Molinetti, A.; Fortini, O.M. Utilization of sediments dredged from marine ports as a principal component of composite material. *J. Clean. Prod.* **2017**, *142*, 4041–4049. [CrossRef]
64. Mymrin, V.; Pan, R.C.Y.; Alekseev, K.; Avanci, M.A.; Stella, J.C.; Scremim, C.B.; Schiavini, D.N.; Pinto, L.S.; Berton, R.; Weber, S.L. Overburden soil and marine dredging sludge utilization for production of new composites as highly efficient environmental management. *J. Environ. Manag.* **2019**, *236*, 206–213. [CrossRef]
65. Liu, J.; Liu, R.; He, Z.; Ba, M.; Li, Y. Preparation and microstructure of green ceramsite made from sewage sludge. *J. Wuhan Univ. Technol. Sci. Ed.* **2012**, *27*, 149–153. [CrossRef]
66. Hamer, K.; Karius, V. Brick production with dredged harbour sediments. An industrial-scale experiment. *Waste Manag.* **2002**, *22*, 521–530. [CrossRef]
67. Liu, R.; Coffman, R. Lightweight Aggregate Made from Dredged Material in Green Roof Construction for Stormwater Management. *Materials* **2016**, *9*, 611. [CrossRef] [PubMed]
68. Colin, D. Valorisation de sédiments fins de dragage en technique routière. Doctoral Dissertation, Université de Caen, Caen, France, 2003.
69. Davidovits, J. Properties of Geopolymer Cements. In Proceedings of the First International Conference on Alkaline Cements and Concretes, Kiev, Ukraine, 11–14 October 1994; pp. 131–149.
70. Wang, D.; Zentar, R.; Abriak, N.E. Durability and Swelling of Solidified/Stabilized Dredged Marine Soils with Class-F Fly Ash, Cement, and Lime. *J. Mater. Civ. Eng.* **2018**, *30*, 04018013. [CrossRef]
71. Natural Resources Conservation Services (NRCS). Hydric Soils—Introduction, (n.d.). Available online: https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/use/hydric/?cid=nrcs142p2_053961 (accessed on 29 November 2020).
72. Dubois, V.; Abriak, N.E.; Zentar, R.; Ballivy, G. The use of marine sediments as a pavement base material. *Waste Manag.* **2009**, *29*, 774–782. [CrossRef]
73. Cantre, S.; Saathoff, F. Investigation of Dredged Materials in Combination with Geosynthetics Used in Dike Construction. *Procedia Eng.* **2013**, *57*, 213–221. [CrossRef]
74. Wang, D.; Abriak, N.E.; Zentar, R. Dredged marine sediments used as novel supply of filling materials for road construction. *Mar. Georesour. Geotechnol.* **2016**, *35*, 472–480. [CrossRef]
75. Yu, H.; Yin, J.; Soleimanbeigi, A.; Likos, W.J. Effects of Curing Time and Fly Ash Content on Properties of Stabilized Dredged Material. *J. Mater. Civ. Eng.* **2017**, *29*, 04017199. [CrossRef]
76. Nguyen, T.T.M.; Rabbanifar, S.; Brake, N.A.; Qian, Q.; Kibodeaux, K.; Crochet, H.E.; Oruji, S.; Whitt, R.; Farrow, J.; Belaire, B.; et al. Stabilization of Silty Clayey Dredged Material. *J. Mater. Civ. Eng.* **2018**, *30*, 04018199. [CrossRef]
77. Maherzi, W.; Abdelghani, F.B. Dredged Marine Sediments Geotechnical Characterisation for Their Reuse in Road Construction. *Eng. J.* **2014**, *18*, 27–37. [CrossRef]
78. Chu, C.; Deng, Y.; Zhou, A.; Feng, Q.; Ye, H.; Zha, F. Backfilling performance of mixtures of dredged river sediment and iron tailing slag stabilized by calcium carbide slag in mine goaf. *Constr. Build. Mater.* **2018**, *189*, 849–856. [CrossRef]
79. Develioglu, I.; Pulat, H.F. Compressibility behaviour of natural and stabilized dredged soils in different organic matter contents. *Constr. Build. Mater.* **2019**, *228*, 116787. [CrossRef]
80. Yozzo, D.J.; Wilber, P.; Will, R.J. Beneficial use of dredged material for habitat creation, enhancement, and restoration in New York–New Jersey Harbor. *J. Environ. Manag.* **2004**, *73*, 39–52. [CrossRef] [PubMed]
81. Clarke, D.; Kasul, R. Value of Offshore Dredged Material Berms for Fishery Resources. In Proceedings of the Dredging'94 International Conference, Lake Buena Vista, FL, USA, 13–16 November 1994; pp. 938–945.
82. Marlin, J.C. Evaluation of sediment removal options and beneficial use of dredged material for Illinois river restoration: Preliminary report. In Proceedings of the Western Dredging Association Twenty-Second Technical Conference and Thirty-Fourth Texas A&M Dredging Seminar, Denver, CO, USA, 15–18 June 2002.
83. Koropchak, S.C.; Daniels, W.L.; Wick, A.; Whittecar, G.R.; Haus, N. Beneficial Use of Dredge Materials for Soil Reconstruction and Development of Dredge Screening Protocols. *J. Environ. Qual.* **2016**, *45*, 62–73. [CrossRef]
84. Mohan, R.K.; Herbich, J.B.; Hossner, L.R. With Dredged Material. *J. Hazard. Mater.* **1997**, *53*, 141–164. [CrossRef]
85. Analysis Potential for Use of Dredged Materials at Landfills, n.d. Available online: https://bcdc.ca.gov/planning/reports/AnalysisPotentialForUseOfDredgedMaterialsAtLandfills1995.pdf (accessed on 30 May 2023).
86. Darmody, R.G.; Marlin, J.C. Illinois River dredged sediment: Characterization and utility for brownfield reclamation. In Proceedings of the 25th Annual Meetings of the American Society of Mining and Reclamation and 10th Meeting of IALR, Richmond, VA, USA, 14–19 June 2008; American Society of Mining and Reclamation: Champaign, UL, USA, 2008; pp. 253–270. [CrossRef]

87. Darmody, R.G.; Marlin, J.C.; Talbott, J.; Green, R.A.; Brewer, E.F.; Stohr, C. Dredged Illinois River Sediments. *J. Environ. Qual.* **2004**, *33*, 458–464. [CrossRef] [PubMed]
88. Diaz, D.R.; Darmody, R. *Illinois River Dredged Sediments and Biosolids Used as Greenhouse Soil Mixtures*; (TR Series (Illinois Waste Management and Research Center); No. TR-038); Waste Management and Research Center: Champaign, IL, USA, 2004.
89. Marlin, J.C.; Darmody, R.G. *Beneficial Use of Illinois River Sediment for Agricultural and Landscaping Application*; Illinois Sustainable Technology Center: Champaign, IL, USA, 2018.
90. Aouad, G.; Laboudigue, A.; Gineys, N.; Abriak, N.E. Dredged sediments used as novel supply of raw material to produce Portland cement clinker. *Cem. Concr. Compos.* **2012**, *34*, 788–793. [CrossRef]