Effect of the amount of river sediment on the basic properties of cement mortars

Tomasz Zdeb[1] , *Tomasz* Tracz[1], and *Marcin* Adamczyk[1*]

[1]Cracow University of Technology, Faculty of Civil Engineering, Chair of Building Materials Engineering, Warszawska St. 24, 31-155 Cracow, Poland

Abstract. According to current legal regulations, bottom sediment in watercourses containing heavy metals are considered dangerous to the environment and should be properly managed after extraction. Due to the well-known excellent ability of the products of cement hydration to immobilize heavy metals, the possibility of utilizing this type of waste products in cement composites was preliminary tested. For this purpose, basic research was carried out on the technological and mechanical characteristics of binders containing sediment from one of the rivers located in Lesser Poland. Standard mortars made of Portland cement CEM I and river sediment dried at 105°C were used for the tests. This supplement replaced cement in the amount of 10%, 20%, 30% and 40% by weight. The technological properties such as: water demand, setting time, consistency and mechanical properties were verified. Compressive and tensile strength at bending of hardened mortars were tested at different curing periods, i.e. after 14, 28 and 90 days. The obtained test results confirm that the fraction of river sediment in the binder in the amount of 10% generally does not adversely affect the properties of mortars, however, its greater amount is reflected in changes in the technological features and in a clear reduction of mechanical properties of the tested mortars.

1 Introduction

Dredging water bodies, including lakes, rivers or ports, is a common process. It helps to restore their natural depth and prevents, among other things, flooding, and, in the case of ports, ensures that ships have a sufficient draft [1]. Deposition of sediment on the bottoms of water bodies is either a natural process (so-called endogenous origin) or frequently is due to human activity (so-called exogenous origin). As a result of these processes, large amounts of sediments with different grain size and chemical composition are extracted [2–4]. In France, for example, the amount of extracted sediments reaches 50 million m^3 per year. For the same time period, 300 million m^3 of sediment is extracted in Europe and the

* Corresponding author marcin.adamczyk@pk.edu.pl

USA [2, 3]. Currently, there is not much guidance on how to manage the waste from dredging. In most cases in the world, these sediments are dumped into the sea as this method is considered easy and economically justified [4]. When considering the problem locally, particular attention should be paid to the criteria for classifying bottom sediments. Several pieces of legislation need to be taken into account when assessing their use, in order to classify them in terms of environmental impact. The main legal acts are: Regulation of the Minister of Environment of 16 April 2002 on types and concentrations of substances which result in the excavated material being designated as polluted [5], Regulation of the Minister of Environment of 9 September 2002 on soil quality standards [6] and Act on Waste of 14 December 2012 [7]. When assessing the environmental impact of bottom sediments, the crucial property is their heavy metal content. The assessment of the degree of sediment contamination allows to determine the direction of their possible use. Thanks to the known ability to immobilize heavy metals in cement composites, mainly due to cement hydration products, it is possible to use them even with high levels of contamination. The idea of this type of management of sediments seems to be correct because, as research shows, these composites have the ability to almost completely immobilize heavy metals [8–11]. The literature extensively describes the manner of utilization of bottom sediments in building materials. They are used as additives to cements [12–14] mortars [3, 4, 15] as well as concrete [16–19]. These deposits are also used in ceramic materials, such as bricks [20, 21] and lightweight aggregate [22, 23]. In addition, they are used as one of the components of road foundations [24, 25].

The aim of the research presented below was to characterize the basic properties of the bottom River Sediment (*RS)* from the Drwina River near the Płaszów Wastewater Treatment Plant in Krakow for its application in cement composites. Its chemical and phase composition, grain size distribution and specific surface area were determined. Furthermore, the basic technological and mechanical properties of mortars using this deposit as a component were tested. Although, on the basis of preliminary research results, it can be concluded that RS is mainly an inert material consisting of fine quartz grains, it was decided to treat it as an additive replacing cement in order to demonstrate the possible influence of its impurities on the technological properties of the obtained binders.

2 Materials and methods

Research on river sediments was carried out based on the example of the already mentioned Drwina watercourse located in Krakow in the Lesser Poland (Małopolska) region of Poland. The studied sediment was dehydrated and dried to solid mass at 105°C. Additionally, few thicker, random grain sizes were separated from it on a 0.5 mm mesh screen. Testing of cement slurries and mortars with RS was carried out using CEM I 42.5 R Portland cement meeting the requirements of the PN EN 197-1 standard. The chemical and phase composition is presented in Table 1.

Table 1. Chemical and phase composition of CEM I 42.5R cement.

Component	**Quantity**
[-]	[% wt.]
Chemical composition	
SiO_2	19.8
CaO	64.6
MgO	1.0
Al_2O_3	4.9
Fe_2O_3	2.7
SO_3	2.9
Na_2O_e	0.48
Cl^-	0.024
P_2O_5	-
LOI	2.9
Phase composition	
C_3S	59.8
C_2S	5.5
C_3A	8.5
C_4AF	8.5
Physical properties	
Blaine [cm^2/g]	3460

During the tests of binders containing RS, slurries and mortars containing 10%, 20%, 30%, and 40% of sediment were made, replacing cement by weight. For testing mechanical properties, the prepared mortars were characterized by a composition with a constant W/C ratio of 0.5 and binder to aggregate ratio of 1:3. All mortars had a similar consistency of approximately 17 cm, as determined by the flow table method according to PN EN 1015-3. The compositions and the exact flow values in relation to the individual compositions are presented in Table 2. The samples were cured under conditions which prevented water evaporation for 14, 28 and 90 days.

Table 2. Normal mortar compositions and their consistency.

Designation	**List of components**				**Consistency**
	Sand	Cement	Water	Sediment	Flow
	[g]	[g]	[g]	[g]	[cm]
REF	1350	450	225	-	16.5
RS 10		405		45	17.0
RS 20		360		90	17.5
RS 30		315		135	17.0
RS 40		270		180	18.5

The scope of tests of cement slurries and mortars was divided into two parts. The first part concerned the characteristics of the sediment used. Among others, the chemical composition was determined by the XRF method using the MiniPal 4 analyzer made by PANalytical B.V., except for the amount of Cl^- ions, SO_3 sulfates and loss on ignition, which were determined according to PN EN 196-2. XRD phase analysis was performed using the Philips PW1830 analyzer. Also, the pozzolanic reactivity of the RS was determined by the Chapelle test. Furthermore, the particle size distribution was characterized by the low-molecular laser diffraction method with the Malvern Instruments Mastersizer 2000 analyzer with the Scirocco 2000 dry measurements attachment. In addition, the development of sediment surface by BET method was analyzed using an automatic gas sorption analyzer Quantachrome Nova 1000e. Photos of the grains of the sediment were taken using the EVO-MA 10 scanning microscope made by Zeiss. The technological properties of binders containing RS, such as water content, setting time and volume stability according to PN EN 196-3 were the focus of the second part of the RS sediment testing. The mechanical properties of these binders, i.e. compressive strength and bending tensile strength, were determined according to PN EN 196-1 after 14, 28 and 90 days of curing with standard mortars.

3 Research results and discussion

3.1 Chemical and physical properties of RS

The results of the chemical and phase composition tests of RS are presented in Table 3 and Fig. 1. Phase composition studies confirmed that quartz remains practically the only crystalline component of RS. This is also reflected in the chemical composition as silicon oxide (SiO_2) represents more than 76% by weight of RS. Additionally, significant amounts of the oxides of aluminum (Al_2O_3) and iron (Fe_2O_3) are observed. The sum of weights of these oxides exceeds 89%, which, on the basis of the criteria adopted for fly ash according to PN EN 450-1, allows us to assume that this material may theoretically exhibit pozzolanic properties. In turn, with reference to the criteria of the same standard, it can be considered that a low total phosphate content (P_2O_5) should not significantly change the setting time of the binders. Although the total content of calcium compounds expressed as CaO was determined at 4%, due to the origin of the material, no risk from delayed hydration of free calcium oxide should be expected in this case. This assumption was fully confirmed in further tests of binder volume stability in the Le Chatelier test. Regardless of the proportion of bottom sediment, all tests showed values below 10 mm. Comparing the proportion of alkali and chloride ions against the criteria adopted for fly ash, the amount of these components remains at a safe level. The loss on ignition, being the sum of the mass of the bound water and the organic part, confirms that the material dried at 105°C is composed solely of mineral origin components.

Table 3. Chemical composition of RS dried at 105°C determined by the XRF method.

Component	Quantity [% wt.]
SiO_2	76.39
Al_2O_3	6.32
Fe_2O_3	6.27
CaO	4.02

P_2O_5	1.19
Na_2O_e	0.61
SO_3	0.5
Cl^-	0.01
LOI	5.20

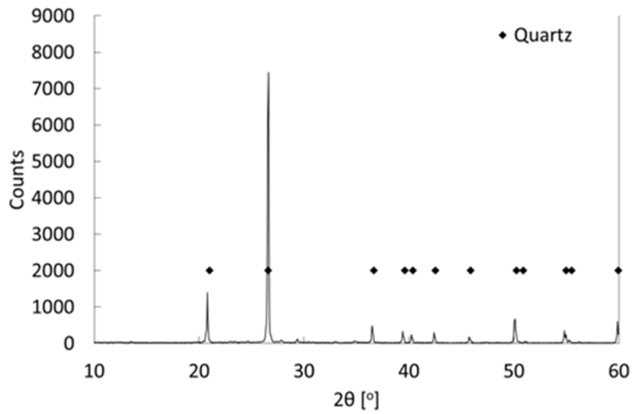


Fig.1 XRD pattern of RS dried at 105°C.

The determination of pozzolanic reactivity using the Chapelle test was performed with respect to the tested RS and also for comparison with silica fume of specific surface area (BET_{SF}=22.4m^2/g). The obtained results confirmed that the RS reactivity value compared to SF is only 5% (RS=86 mg/g, SF=1751 mg/g). This low reactivity results mainly from the crystalline and thus inert form of silica, i.e. β-quartz. Furthermore, the tested RS is characterized by a relatively small specific surface area (BET_{RS}=1.6m^2/g) in comparison with other known pozzolanic additives such as SF or FA fly ash (BET_{SF}≈20m^2/g, [26] BET_{FA}≈8m^2/g [27]). In summary, the tested material consists mainly of quartz sand grains with a grain size range between 3 and 2000 µm at d_{50} of 330 µm, with a negligible reactivity to cement slurry components.

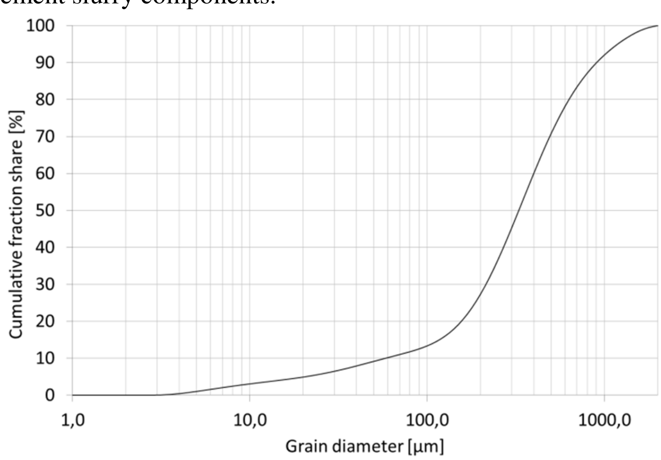


Fig. 2 RS grain size distribution.

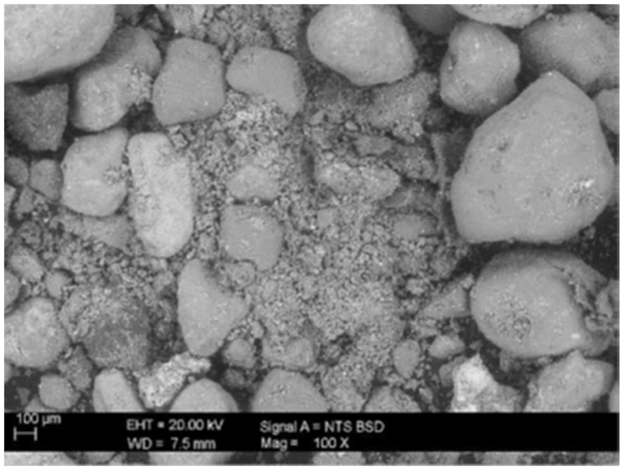


Fig. 3 SEM image of river sediment grains.

3.2 Technological properties of binders

The water demand of binders containing the river sediment was determined by replacing the weight of cement by 0%, 10%, 20%, 30%, and 40% respectively. The results are presented in Fig. 4. RS, due to its composition, which is mainly contaminated sand with a lower specific surface area compared to the cement used, caused a gradual decrease in water demand with its increasing proportion. In the case of the maximum, i.e. 40% proportion of the sediment, the indicated water demand of the binder in relation to the reference value was lower by 7.8%.

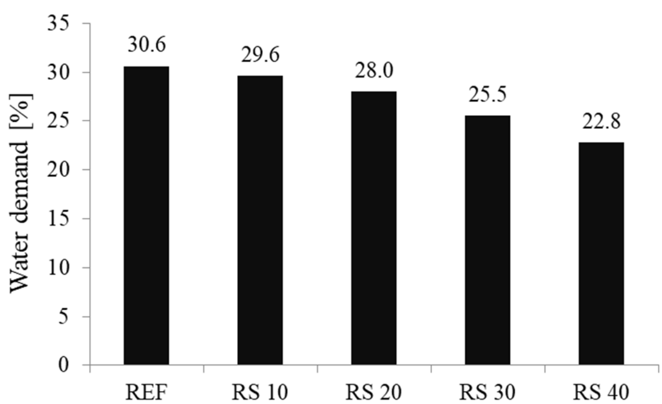


Fig. 4 Water demand of binders containing RS.

Due to the presence of 1.2% of phosphates in the RS tested, the effect of this additive was determined in the range of 0 to 40% of cement substitution with sediment at the start and end of the binder setting process. The results are presented in Fig. 5. The proportion of RS of up to 30% of the binder weight results in a continuous but insignificant increase of the setting time. In this case, i.e. when the cement weight is replaced by RS in the amount of 30%, an extension of the start time by almost 40% is observed. In turn, the end of setting was extended slightly less, by approx. 20%. A steep increase in setting times was demonstrated by the binder containing 40% of bottom sediment. Both the beginning and the end of the setting was extended more than twice compared to the reference value. One of the reasons for this rapid extension of setting times may be an increase in the mutual distance between cement grains and thus a reduction in the possibility of bridging between them from the formation of cement hydration products.

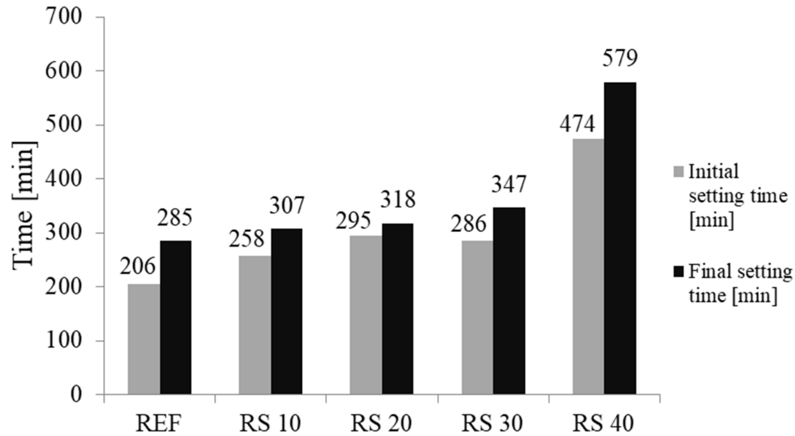
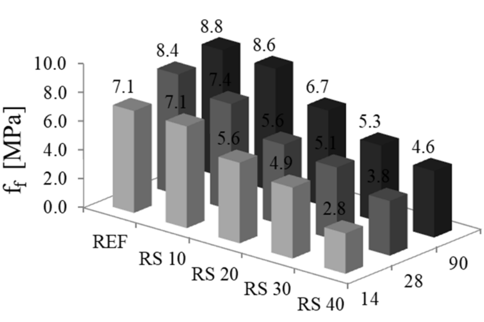


Fig. 5 Setting time for binders containing RS.

3.3 Mechanical properties

The results of the mechanical properties tests are presented in Figs. 6 – 9. The most important observations include the fact that regardless of the level of cement replacement by RS, a longer curing period did not result in a decrease in strength, and even a moderate increase up to 90 days.



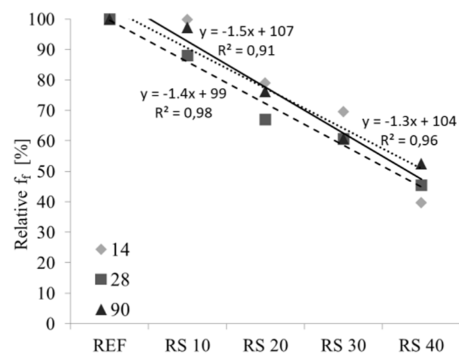


Fig. 6 Bending tensile strength for specific curing periods and levels of cement replacement by RS.

Fig. 7 Relative bending tensile strength for specific curing periods and levels of cement replacement by RS with linear regression.

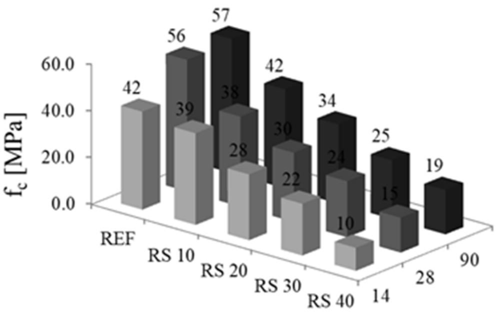


Fig. 8 Compressive strength for specific curing periods and levels of cement replacement by RS.

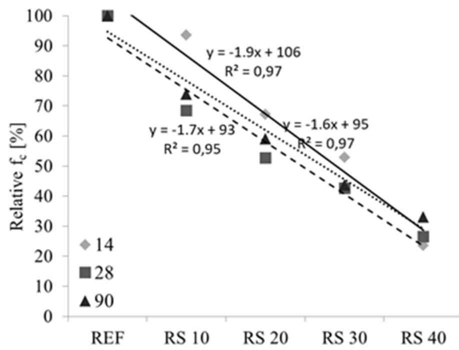


Fig. 9 Relative compressive strength for specific curing periods and levels of cement replacement by RS with linear regression.

In the case of bending tensile strength, we observe a consistent and almost linear decrease with increasing amounts of the additive. An increase in the amount of RS in the binder by each 10% results in a decrease in bending tensile strength of 14%, on average. Similar values are observed regardless of the curing time of the mortars tested. With regard to compressive strength, the increasing share of RS is not conducive to the development of this property. There is a more pronounced decrease here than in bending strength, but still linear. The most pronounced reduction in compression strength was recorded for a short 14-day curing period. Then, for every 10% of the increasing share of river sediment in the binder, the average decrease amounts to 19%. After 28 days of curing, the reduction is slightly lower, averaging 17%, while after 90 days of curing, the reduction in compressive strength is the lowest, approx. 16%.

4 Conclusion

The safe disposal of the bottom sediment from the Drwina River in cement composites naturally requires an extension of the research program to include an analysis of the leachability of heavy metals in relation to both mortars and, in the future, concrete. This article focuses on the description of selected properties of RS as well as on the basic properties of cementitious mortars containing this additive. As the results showed, the studied material consists mainly of contaminated, fine-grained quartz sand of an inert nature. It does not fundamentally change the technological properties of the binder in up to 30% proportion by weight. However, its presence in the binder clearly reduces mechanical properties, what the reasons should be found in the composition of the sediment. Its introduction, in fact causes an increase in the aggregate content and a simultaneous reduction in the cement content. For every 10% increase in RS, an average decrease in compressive strength of 17% and in bending tensile strength of about 14% was recorded. In connection with the obtained test results, it still seems necessary to carry out tests on composites obtained by replacing fine aggregate with river sediment and to verify them in terms of technological and mechanical properties as well as heavy metal leaching.

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