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Statistical analyses of sustainable cement mortars mechanical strength

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Abstract:
Sediment dredging involves the release of huge volumes of materials, whose management is one of the priority issues to be addressed to limit landfilling. Reuse options for dredged materials must be identified, following their characterization; according to the circular economy principles and in compliance with the Agenda 2030 provisions, one of the most promising is using sediments to make cement conglomerates. From sediments sampled from the Camastra and San Giuliano reservoirs, located in Basilicata, a region in southern Italy, cement mortars have been obtained, first by completely replacing the aggregate with sandy downstream material in varying quantities and then also by partially replacing the binder in constant quantities. In the present work, the relationship between the amount of sandy aggregate replaced in mortars and the compressive strength of the mortars is investigated by statistical analysis. The compressive strengths found for the SG_s1 (60 MPa) and SG_s2 (52 MPa) specimens are significant, as they are approximately 15% higher than the normalized mortar, the reference. On the contrary, all mortars prepared with the Camastra sediments exhibit compressive strengths approximately 50% lower than the normalized mortar. Statistical analyses show that the compressive strengths depend on the content of sandy material used, concerning the specimens in which only the aggregate was entirely replaced by the downstream sediment. In contrast, if the upstream clay material is used instead of part of the binder, there is no statistical

correlation between the compressive strength values and the content of the sandy material used.

Keywords:
Dredged sediments, Waste valorisation, Sediment reuse, Cementitious materials, Compressive resistance.

1. Introduction

The phenomenon of reservoir silting represents one of the main critical issues in the context of reservoir management, with rates that, in some cases, have already reached, if not exceeded, 50% of the useful design capacity (RANDLE *et al*., 2021; NIU & SHAH, 2021; ASHTANA *et al*., 2022). As a result, the need for dredging becomes a priority in management operations, having the downside of generating a large amount of sediment that, without a reuse alternative, will have to be landfilled (MORRIS, 2020). As such, the identification of reuse scenarios is a key element in preserving the environment from any adverse effects that disposal normally generates (ANARI *et al*., 2023).
In addition, the valorisation and the recovery of sediments, could make it possible to have a local resource both environmentally friendly, and economically extremely convenient (HUSSAIN *et al*., 2022; DJERAN-MAIGRE *et al*., 2022; SOLEIMANI *et al*., 2023; HUSSAN *et al*., 2023). Furthermore, the impacts associated with dredging activities, tend to be mitigated if the material is included in a valorisation process, limiting the environmental damage associated with the disposal.
An analysis of the scientific literature reveals studies carried out on the hypothesis of recycling sediments in the manufacture of sustainable cementitious materials, through the replacement of the aggregate (- ANGER *et al*., 2019; CHU *et al*., 2022). Thus, the use of sediment as a secondary raw material makes it possible to reduce the consumption of non-renewable resources and the carbon footprint associated with the mortar production process (SEIFI *et al*., 2019).
This study analyses the possible reuse of sediments from two artificial reservoirs in southern Italy, the Camastra and the San Giuliano, in the Basilicata region. The granulometric characterisation showed that, for both reservoirs, the sediments sampled from the upstream areas present a predominant clayey matrix; on the contrary, the sandy component prevails in the sediments coming from the downstream areas. Therefore, the upstream and downstream sediments for each reservoir were grouped together in a single sample and used to make sustainable cement mortars. These were partly obtained by completely replacing the aggregate, in varying quantities, with the downstream sediment; in addition, others were made by also replacing part of the binder, in a constant quantity, with the upstream clay sediment. All the mortars, prepared without preliminary treatments, were subjected to compressive strength tests and the results were compared to each other, assessing their suitability for reuse (TODARO *et al*., 2023). Finally, by

statistical tests, it was investigated whether a correlation existed between the amount of sandy aggregate substituted in the mortars and the mechanical strength exhibited in the laboratory tests.

2. Materials and methods

The sediments used in the cement mortars were collected from two reservoirs in southern Italy, the Camastra and the San Giuliano, located in the Basilicata region.
The sampled materials were subjected to granulometric analyses, which showed that the sediments coming from the upstream areas of the reservoirs are all characterised by a predominantly clayey matrix, while those taken from the downstream areas exhibit a more marked sandy component, the latter exceeding 53% in the San Giuliano samples and approximately 45% in those from the Camastra (MARTELLOTTA *et al*., 2023). Due to this evidence, the sediments of each reservoir were grouped according to their origin from upstream or downstream areas, naming these groups C_D (Camastra downstream), C_U (Camastra upstream), SG_D (San Giuliano downstream) and SG_U (San Giuliano upstream).
The available material was used for the preparation of the mortars, using the downstream sediment in total replacement of the sandy aggregate, in varying quantities, and the upstream sediment in partial replacement of the binder, in constant quantities (see Tables 1 and 2).

Table 1. Camastra sediment-based mortars composition.

Specimen	*Cement (g)*	*Water (g)*	*Sand (g)*	*Clay (g)*
Normalized mortar	*450*	*225*	*1350*	*0*
C_s1	*450*	*225*	*400 **	*0*
C_s2	*450*	*225*	*325 **	*0*
C_s3	*450*	*225*	*250 **	*0*
C_s5	*450*	*225*	*175 **	*0*
C_s1&c	*350*	*225*	*400 **	*100 ***
C_s2&c	*350*	*225*	*325 **	*100 ***
C_s3&c	*350*	*225*	*250 **	*100 ***
C_s5&c	*350*	*225*	*175 **	*100 ***
C_s6&c	*350*	*225*	*100 **	*100 ***

*Note: * material mainly assimilated to sand (2000 μm > Ø > 63 μm); ** material mainly assimilated to clay (Ø < 2 μm).*

Table 2. San Giuliano sediment-based mortars composition.

Specimen	***Cement (g)***	***Water (g)***	***Sand (g)***	***Clay (g)***
Normalized mortar	*450*	*225*	*1350*	*0*
SG_s1	*450*	*225*	*550 **	*0*
SG_s2	*450*	*225*	*475 **	*0*
SG_s3	*450*	*225*	*400 **	*0*
SG_s4	*450*	*225*	*325 **	*0*
SG_s5	*450*	*225*	*250 **	*0*
SG_s3&c	*350*	*225*	*400 **	*100 ***
SG_s4&c	*350*	*225*	*325 **	*100 ***
SG_s5&c	*350*	*225*	*250 **	*100 ***
SG_s6&c	*350*	*225*	*175 **	*100 ***
SG_s7&c	*350*	*225*	*100 **	*100 ***

*Note: * material mainly assimilated to sand (2000 µm > Ø > 63 µm); ** material mainly assimilated to clay (Ø < 2 µm).*

The binder (cement CEM II A-LL 42.5 R, Buzzi Unicem, Barletta, Italy) and the water, supplied by the local concessionaire (AQP SpA), drinking and suitable for use in construction activities, were added to the sediment (UNI EN 197-1). In addition to the sediment-based mortars, a control conglomerate, the normalised mortar, was prepared using the same binder and water, with the addition of normalised sand (~1700 kg/m^3, 0.08-2 mm, Societé Nouvelle du Littoral, Leucate, France), having grains in the range between 0.5 and 1 mm after sieving, in place of the sediment (UNI EN 197-1).
The correct water content was determined by defining the water content of the sediment; the operational procedure involved the use of an oven, in which 50 g of sediment from both reservoirs was heated to a temperature of 50 °C. Therefore, by varying the amount of sandy aggregate, the mortars named C_s1, C_s2, C_s3, C_s5, SG_s1, SG_s2, SG_s3, SG_s4, and SG_s5 (C stands for 'Camastra' reservoir; SG stands for 'San Giuliano' reservoir) were obtained. Subsequently, again by changing the amount of sandy aggregate and, at the same time, replacing 100 g of binder with the upstream sandy material, the mortars named C_s1&c, C_s2&c, C_s3&c, C_s5&c, C_s6&c, SG_s3&c, SG_s4&c, SG_s5&c, SG_s6&c, and SG_s7&c were manufactured.
The determination of the percentage of sandy material used in each mortar was carried out by means of the aggregate ratio α defined by equations (1) and (2) below; in particular, equation (2) refers to mortars obtained by also replacing part of the binder with downstream clay material:

$$\alpha = \frac{s_m}{c + s_m + w} \quad (1)$$

$$\alpha = \frac{s_m}{c + s_m + c_m + w} \quad (2)$$

where s_m is the mass of the sandy material, c is the mass of the cement, c_m is the mass of the clayey material, and w is the mass of the water.
For the determination of the compressive strength, 20 prismatic specimens (19 sediment-based mortars and 1 normalized mortar) with dimensions of 40 mm x 40 mm x 160 mm were prepared and, after 28 days of curing at room temperature (20 °C ± 2 °C), were subjected to a compression test (MATEST, Milan, Italy), conducted by increasing the load at intervals of 2400 ± 200 N/s, until failure (UNI EN 196-1).
The compressive strength values were subjected to statistical analysis to investigate the possible correlation between the compressive ultimate strength and the amount of sandy material. The null hypothesis H_0 verified with the statistical tests was the following: the mechanical strength is not influenced by the amount of aggregate. The p-value, conventionally assumed to be 0.05, expresses the level of statistical significance; the lower the p-value, the greater the probability that the null hypothesis is not verified. In this case, first the Shapiro-Wilk W test was used to ascertain whether the sample exhibits Gaussian distribution (SHAPIRO & WILK, 1965; ROYSTON 1992), using equation (3).

$$p = \frac{\left(\sum_{i=1}^{n} a_i w_{(i)}\right)^2}{\sum_{I=1}^{n} (w_i - \overline{w})^2} \quad (3)$$

where $w_{(i)}$ (index i included in brackets) is the smallest value of each parameter detected within the sample (order i); $\overline{w} = \frac{(w_1 + \ldots + w_n)}{n}$ is the arithmetic average of the values detected for each parameter within the examined sample; the constant a_i is derived from equation (4):

$$a_i = \frac{m^T V^{-1}}{(m^T V^{-1} V^{-1} m)^{1/2}} \quad (4)$$

where $m = (m_1 \ldots, \ldots m_n)$ are the expected values of the ranks of a standardised random number and V is the matrix of covariances of these ranks.
The data follow a Gaussian distribution, therefore, the homogeneity of the variances of the investigated samples was verified with Fisher's exact test, from which it follows that the observed differences within the sample data vectors are simply due to chance (UPTON, 1992; CONNELLY, 2016). As the variances were found to be homogeneous, the application of Student's t-test allowed us to compare the averages of the considered data sets, which are independent of each other, and to check whether they differ from each other randomly or not (EFRON, 1969; DE WINTER, 2013).

3. Results and discussion

3.1 Data focus

Tables 1 and 2 define the composition of the sediment-based mortars from the Camastra and San Giuliano reservoirs, respectively. For each table, a distinction was made between the specimens obtained by substituting only the aggregate with the downstream sandy material and those obtained by also substituting the upstream clayey material for part of the binder, in a fixed percentage of 22.2%.

3.2 Compressive strength performance

The two semi-prisms obtained from each specimen by flexural strength test, were subjected to a compressive strength test. The breaking values were represented in Figure 1, where the compressive strength R_c in MPa is plotted on the Y-axis and all values are compared to those of the normalised mortar.

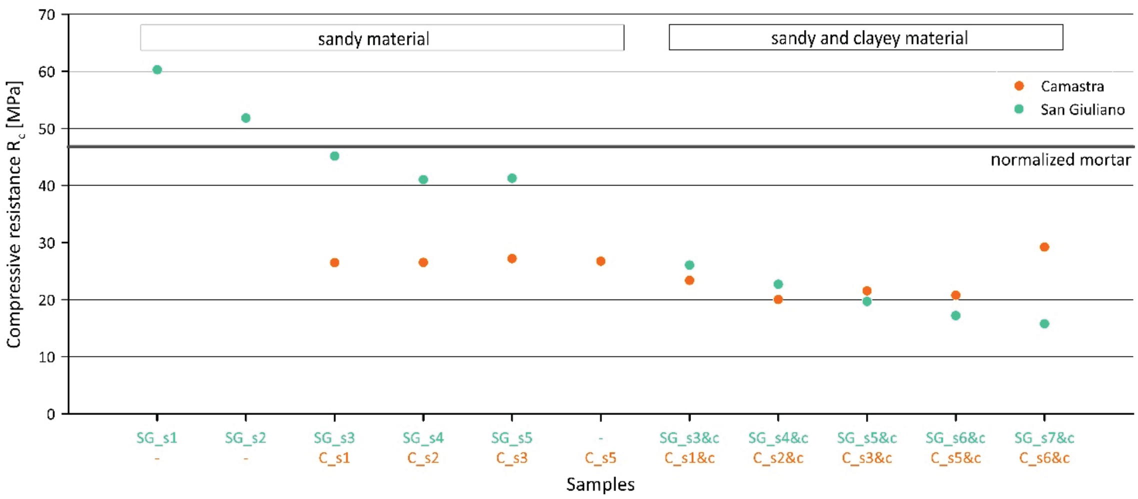


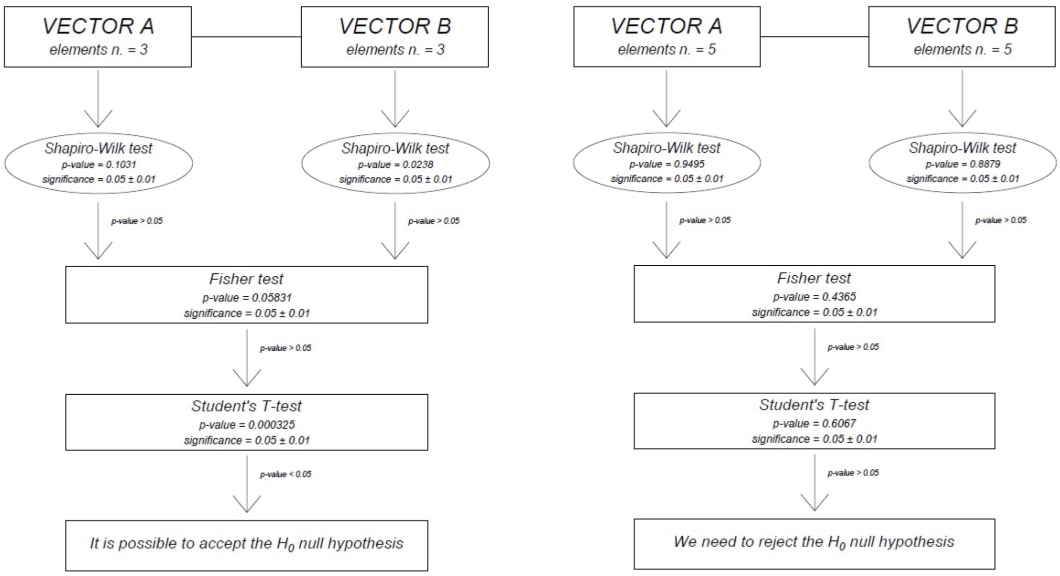
Figure 1. Compressive strength of mortars obtained from the Camastra (orange dots) and San Giuliano (green dots) sediments.

In the case of the mortars based on the Camastra sediments, the compressive strength values are all less than 30 MPa and are approximately half the value of the normalised mortar. Among all the mortar specimens, the one with the highest compressive strength value is the C_s6&c specimen (approximately 29 MPa); at the same time, the highest average values, approximately 27 ± 0.3 MPa, are found for the specimens in which only the sandy aggregate was substituted, on the contrary, in the others, an average value of approximately 23 ± 3.7 MPa is found.

For the San Giuliano sediment-based mortars, the average compressive strength value of 48.0 ± 8.1 MPa is higher if only the sandy aggregate is replaced, on the contrary, it is reduced to 19.8 ± 3.7 MPa if part of the binder is also substituted. In addition, the

compressive strength tends to decrease as the content of sandy aggregate in the mortars decreases. The SG_s1 and SG_s2 specimens, show a compressive strength higher than that of the normalised mortar, by approximately 15%.
Higher percentages of sandy aggregate correspond to higher strengths; this is always verified in the case of the San Giuliano sediment-based mortars, even when replacing part of the binder. For the Camastra sediment-based mortars, however, no such correlation is found.

3.3 Statistical analysis
It was verified whether a relationship existed between the amount of sandy material used and the compressive strengths exhibited in the compression fracture tests; the results of the evaluations conducted are shown in Figure 2.



(a) (b)

Figure 2. Test results for the specimens in which only the aggregate was replaced (a) and for the specimen in which both the aggregate and part of the binder were replaced (b).

Analyses using the Shapiro-Wilk W test showed that the data have a normal distribution (p-value > 0.05), so Fisher's test was used to assess the homogeneity of the variances. Since the p-value was greater than 0.05, the sample variances are homogeneous, so Student's t-test was used to test whether the null hypothesis H_0 (mechanical strength is not affected by the amount of aggregate) could be rejected. The null hypothesis is acceptable if the p-value is greater than 0.05, so it is noted that it is not verified for mortars obtained by aggregate replacement alone. (On the contrary, if part of the binder is

replaced by the clayey upstream sediment, it is necessary to accept the alternative hypothesis H_1.
Ultimately, the statistical analyses carried out show that the mechanical strength of mortars is significantly related to the amount of aggregate that makes up each mix, although this relationship is lost when even part of the binder is replaced with upstream clay material.

4. Conclusions

The study shows that the mechanical strengths of almost all manufactured mortars are, in general, lower than those of normalised mortar, with significant reductions when part of the binder is replaced by upstream clay material. Specifically, the mortars obtained from the Camastra sediments exhibit a lower average compressive strength than the conglomerates based on the sediments of San Giuliano reservoir. Consequently, it is deduced that the use of materials dredged from the Camastra as aggregate is not recommended, as they exhibit a predominantly binder-like behaviour. The compressive strength tends to decrease as the content of sandy material in the mix decreases and, above all, as part of the binder is replaced by the upstream clayey sediment. Therefore, as the mechanical strengths are mainly explicated by the aggregate, the materials dredged from the San Giuliano reservoir exhibit a more marked aggregate behaviour.
In conclusion, the reuse of sediments in the manufacture of cement mixes is a viable alternative to landfilling, consistent with the principles of the circular economy. In fact, this contributes to decreasing the consumption of virgin material, a non-renewable resource, as well as limiting the carbon footprint associated with the construction materials production cycle. In addition, sediment-based mortars are an environmentally sustainable material, as they can be obtained without pre-treatment and with reduced water consumption, as part of the water is already included in the sediment. Thus, the sediment becomes a profitable local resource with multiple benefits, both environmental and economic, by being part of an existing production chain that can be positively modified.

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