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# Mechanical Properties of Soil-cement Composites Made with Cohesive or Non-Cohesive Soil

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**Abstract** The paper discusses results of mechanical and technological tests of soil-cement composites made with cohesive or non-cohesive soil. The compositions of the soil-cement mixtures analysed differed in terms of their cement paste volume fractions and water-cement ratios. Limiting values of these technological parameters that enable the application of the soil-cement mixtures obtained in real life conditions for the purposes of the Deep Soil Mixing (DSM) method were determined. Based on the test results obtained, it was found that mechanical properties of the materials analysed were very sensitive to changes in their compositions. Variations in the volume fraction of cement paste within the range analysed caused mechanical properties to change even by an order of magnitude.

## 1. Introduction

The increasing rate at which new projects are being constructed under increasingly difficult soil conditions necessitates the continuous development of geotechnical engineering. In recent years, the leading method in this respect has been reinforcing weak soil substrate. The development of soil improvement techniques and of the technologies related to the materials used in geotechnical engineering has given rise to a number of methods used for reinforcing soil. Among those, those solutions are selected which have the least harmful impact on the environment, are simple to implement and involve low implementation costs. Methods which are quick and thus shorten the time needed to complete the entire project are also in demand. In-situ soil mixing has been developed in response to these requirements. This method enables soil properties to be modified directly without the need to bring the material to the surface. Mechanical properties of soil are improved as a result of mixing it with a binding material which can be fed in the form of either a “wet” paste or a “dry” powder. This material enters into a chemical reaction with the soil and the water retained within it, creating a new material with an altered composition and the desired mechanical properties. This binding material is referred to as the stabiliser. Its choice depends on, *inter alia*, the type and condition of the soil to be reinforced and on the manner in which the stabiliser is added to the soil. Therefore, many materials or mixtures are currently used as stabilisers. Most common ones, however, include mineral binders, chiefly various types of cement [1, 2]. It may be stated that mixing the substrate with a stabiliser will result in its reinforcement for almost all types of soil, both non-cohesive and cohesive. However, the degree to which this reinforcement is effective will certainly vary. Thus, apart from selecting the proper binder, its appropriate amount must also be determined on the basis of specific soil conditions [3, 4]. The author of [1] points out that any predictions of mechanical properties of reinforced soil on the basis of soil type evaluation and the amount and type of the binder used should



be preceded by proper laboratory tests. Requirements of the in-situ soil mixing technology should also be accounted for during the design process. In response to these requirements, this paper presents the results of tests concerning selected properties of hardened composites (so-called soil-cements) obtained by mixing both non-cohesive and cohesive soils with cement paste and evaluates them in terms of their practical application during the process of designing soil substrate reinforcements.

## 2. Materials

The research programme involved producing multiple series of soil-cement composites whose compositions varied in terms of the type of the soil being reinforced, the amount of cement paste  $V_z$  used and water-cement (w/c) ratios. Two significantly different types of soil were selected: cohesive soil (identified as loam) and non-cohesive soil, which was medium sand. The soil-cement compositions tested were created as a result of mixing the virgin soils described in Table 1 with CEM II/B-S 32.5 R cement paste with the properties stated in Table 2.

**Table 1.** Properties of the soils selected

Properties	Medium sand values	Loam values
Particle size distribution [% by mass]		
- gravel fractions 2/40 mm	5	-
- sand fractions 0.05/2 mm	95	30
- dust fractions 0.002/0.05 mm	-	42
- loam fractions <0.002 mm	-	28
Bulk density $\rho$ [g/cm <sup>3</sup> ]	1.60	2.08
Bulk density of the soil skeleton $\rho_d$ [g/cm <sup>3</sup> ]	1.56	1.79
Maximum bulk density of the soil skeleton $\rho_{dmax}$ [g/cm <sup>3</sup> ]	1.86	1.80
Natural moisture content $w_{n\ sr}$ [%]	2.76	16.1
Optimal moisture content $w_{opt}$ [%]	8.5	18.3
Yield point $w_p$ [%]	-	11.21
Liquid limit $w_L$ [%]	-	37.80
Plasticity index $I_L$ [%]	-	0.18
Approximate content of CaCO <sub>3</sub> [%]	<1	1–3

**Table 2.** Properties of CEM II/B-S 32.5 R cement

Properties	Value
Compressive strength after 2 days [MPa]	18.0
Compressive strength after 28 days [MPa]	49.0
Initial setting time (time of set) [min]	190
Water at normalised consistency [%]	28
Specific surface area [cm <sup>2</sup> /g]	3.570

## 3. Results and Discussions

Owing to the considerable range of properties exhibited by the soils selected for the tests, components were mixed so as to obtain, in each case, mixtures with the desired homogeneity which is similar to that of the mixtures obtained during deep soil mixing on a technical scale. Owing to the peculiar process in which soil-cement is produced when using soil reinforcement technologies, the criterion of proper consistency (workability) of the soil-cement mixture was based on requirements partly similar to those applicable to self-compacting concrete mixes. At the same time, no segregation of mixture

components or bleeding was allowed. It should also be noted that when designing the composition of cement paste (the w/c ratio), the amount of water resulting from natural soil humidity was taken into account.

In the case of non-cohesive soils, the range of cement paste volumes used was from 350 to 500  $\text{dm}^3/\text{m}^3$ , while for cohesive soils this range was from 650 to 800  $\text{dm}^3/\text{m}^3$ . The w/c ratio value ranged from 0.4 to 3.4 for non-cohesive soil and from 1.4 to 4.6 for cohesive soil. Changes in the amount of paste added and in the w/c ratios adopted involved differences in cement content for each mixture (in  $\text{kg}/\text{m}^3$ ). In the case of the soil-cement mixtures tested, cement content ranged from 99 to 542  $\text{kg}/\text{m}^3$  for non-cohesive soil and from 138 to 416  $\text{kg}/\text{m}^3$  for cohesive soil.

**Table 3.** Map of workability of soil-cement composites made with non-cohesive soil

		w/c	3.4	3.2	3.0	2.8	2.6	2.4	2.2	2.0	1.8	1.6	1.4	1.2	1.0	0.8	0.6	0.4
$V_z [\text{dm}^3/\text{m}^3]$	500	-	-	-	-	-	-	-	-	-	-	-	-	-	+	+	+	X
	450	X	-	-	-	-	-	-	-	+	+	+	+	+	+	+	+	X
	400	X	+	+	+	+	+	+	+	+	+	+	+	-	-	-	-	-
	350	X	+	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	mixture consistency – too liquid, significant sedimentation, significant bleeding																	
-	mixture consistency – too thick, not self-compacting																	
+	mixture consistency – proper, no sedimentation, no bleeding																	
X	strength too low, w/c > 3.2																	
X	cement consumption not cost-effective, w/c ratio < 0.6, cement content > 542 $\text{kg}/\text{m}^3$																	

**Table 4.** Map of workability of soil-cement composites made with cohesive soil

		w/c	4.6	4.4	4.2	4.0	3.8	3.6	3.4	3.2	3.0	2.8	2.6	2.4	2.2	2.0	1.8	1.6	1.4
$V_z [\text{dm}^3/\text{m}^3]$	800	-	-	-	-	-	-	-	-	+	+	+	+	+	+	+	+	+	X
	750	X	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	-	-
	700	X	+	+	+	+	+	+	+	+	+	+	+	+	-	-	-	-	-
	650	X	+	+	+	+	-	-	-	-	-	-	-	-	-	-	-	-	-
-	mixture consistency – too liquid, significant sedimentation, significant bleeding																		
-	mixture consistency – too thick, not self-compacting																		
+	mixture consistency – proper, no sedimentation, no bleeding																		
X	strength too low, w/c > 4.4																		
X	cement consumption not cost-effective, w/c ratio < 1.6, cement content > 416 $\text{kg}/\text{m}^3$																		

The scope of soil-cement tests covered the following properties: consistency determined on the basis of the mixture flow diameter measured by means of a flow table, tensile strength determined for 100x100x500 mm prisms and compressive strength determined for 100 mm cubes cut from prism halves after bending. Tests of mechanical properties were conducted after 28 days of curing under laboratory conditions that prevented the evaporation of mixing water.

Fresh mix consistency tests were carried out in accordance with the standard [5]. This method consists in measuring the flow diameter of mixture after shaking it several times on a table. Analysing the measurements conducted, it can be stated that in the case of the soils tested, mixtures with the appropriate consistency exhibited flow diameter values ranging from 150 to 270 mm.

Mechanical properties of hardened composites were tested for 22 soil-cement compositions formed using non-cohesive soil and for 37 soil-cement compositions formed using cohesive soil. The compositions tested were selected on the basis of the consistency assessment conducted. Mixtures which did not meet the required criteria were rejected.

The flexural tensile strength test was conducted in accordance with the standard [6], which concerns testing concrete specimens placed on supporting pins with the constant spacing  $l$  equal to  $3d$ , i.e. 300 mm. The only deviation from the guidelines included in the standard was the reduction in the stress increase rate during the test to 0.01 MPa/s due to the differences in the expected strength of the material tested compared to the tensile strength of normal concrete. Flexural strength ( $f_{cf}$ ) results for soil-cements made using non-cohesive soil are summarised in Table 5 and those for cohesive soil are present in Table 6. Owing to the number of tests performed, partial results are not presented, and the results presented are limited to mean values from three measurements.

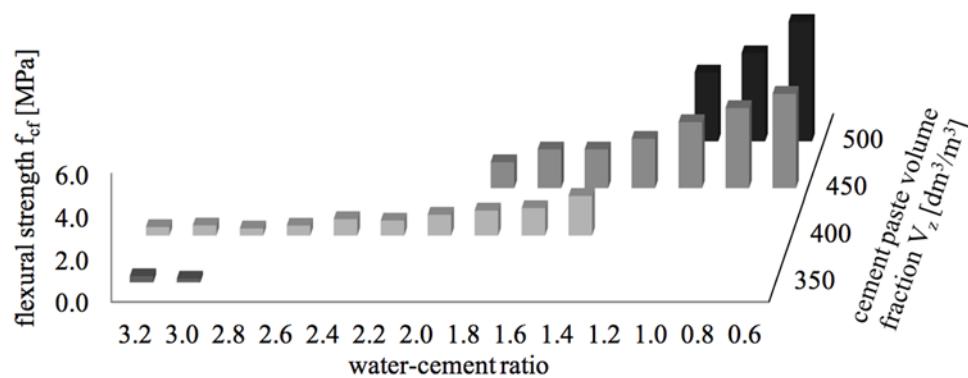
**Table 5.** Results of flexural strength ( $f_{cf}$ ) tests for specimens made with non-cohesive soil after 28 days of curing [MPa]

w/c	3.2	3.0	2.8	2.6	2.4	2.2	2.0	1.8	1.6	1.4	1.2	1.0	0.8	0.6
V <sub>z</sub> [dm <sup>3</sup> /m <sup>3</sup> ]	500											3.2	4.1	5.6
	450							1.2	1.6	1.8	2.3	3.1	3.8	4.4
	400	0.4	0.5	0.3	0.5	0.8	0.7	1.0	1.2	1.3	1.8			
	350	0.3	0.2											

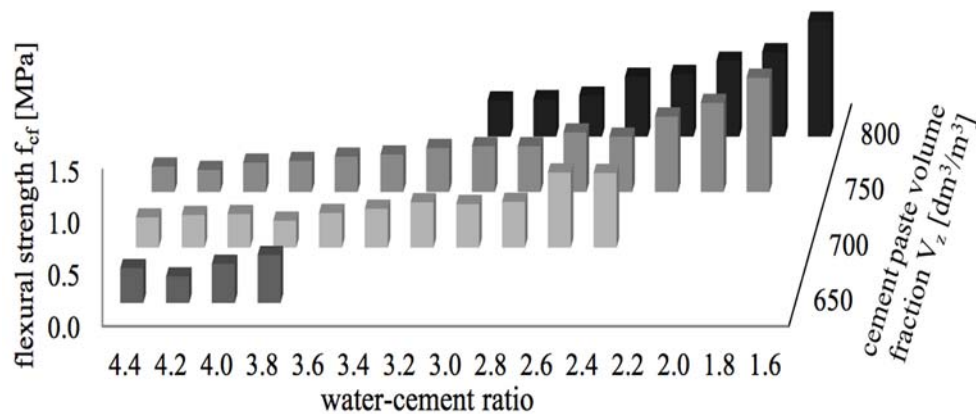
**Table 6.** Results of flexural strength ( $f_{cf}$ ) tests for specimens made with cohesive soil after 28 days of curing [MPa]

w/c	4.4	4.2	4.0	3.8	3.6	3.4	3.2	3.0	2.8	2.6	2.4	2.2	2.0	1.8	1.6	
V <sub>z</sub> [dm <sup>3</sup> /m <sup>3</sup> ]	800								0.3	0.4	0.4	0.6	0.6	0.7	0.8	1.1
	750	0.2	0.2	0.3	0.3	0.3	0.4	0.4	0.4	0.4	0.6	0.5	0.7	0.9	1.1	
	700	0.3	0.3	0.3	0.3	0.3	0.4	0.4	0.4	0.4	0.7	0.7				
	650	0.3	0.3	0.4	0.5											

The charts below (Figure 1 and Figure 2) show the effect of cement paste amount and of the w/c ratio on the flexural tensile strength of soil-cements based on non-cohesive and cohesive virgin soil after 28 days of curing.



**Figure 1.** Flexural strength chart for specimens made with non-cohesive soil depending on the water-cement ratio and cement paste volume fraction after 28 days of curing



**Figure 2.** Flexural strength chart for specimens made with cohesive soil depending on the water-cement ratio and cement paste volume fraction after 28 days of curing

The flexural tensile strength values obtained after 28 days of curing ranged from 0.2 to 5.6 MPa for non-cohesive soil and from 0.2 to 1.1 MPa for cohesive soil. The analysis of results points to an increase in flexural strength achieved by soil-cement as the w/c ratio decreases. Additionally, it was observed that as the amount of cement paste added  $V_z$  decreased for a given w/c ratio, there was a slight increase in the flexural strength of the soil-cement mixtures tested.

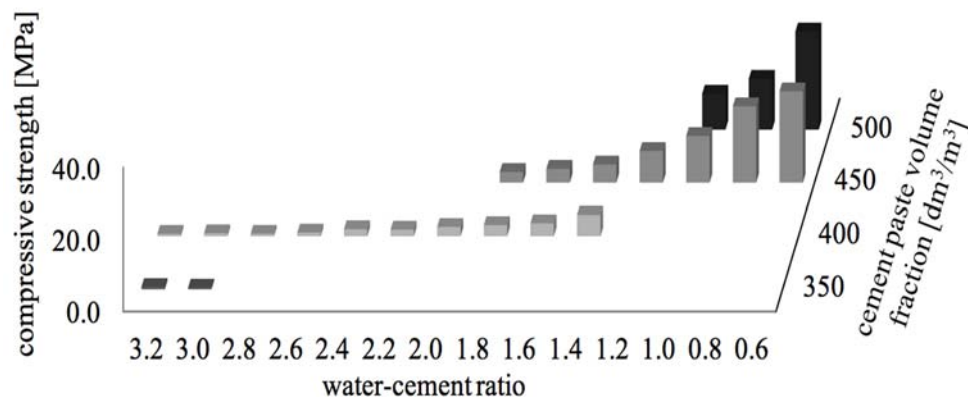
The compressive strength test was conducted in accordance with the standard [7], which also concerns testing concrete specimens. Again, the only deviation from the guidelines included in the standard was the reduction in the stress increase rate during the test to 0.05 MPa/s. Compressive strength ( $f_c$ ) results are summarised in Table 7 for non-cohesive soil and in Table 8 for cohesive soil. Similarly as before, the results presented are mean values from three measurements.

**Table 7.** Results of compressive strength ( $f_c$ ) tests for specimens made with non-cohesive soil after 28 days of curing [MPa]

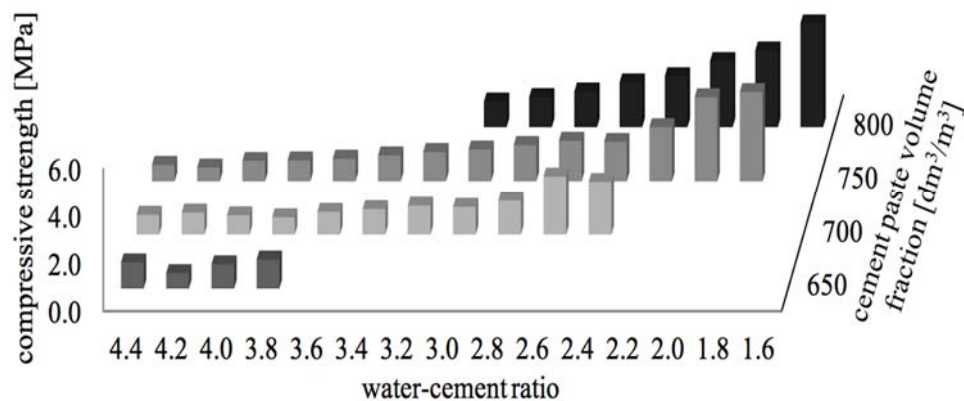
w/c	3.2	3.0	2.8	2.6	2.4	2.2	2.0	1.8	1.6	1.4	1.2	1.0	0.8	0.6					
V <sub>z</sub> [dm <sup>3</sup> /m <sup>3</sup> ]	500												10.0	14.2	27.4				
	450												3.0	3.9	5.1	8.9	13.0	21.4	25.5
	400	0.7	0.9	0.7	1.1	2.0	1.9	2.6	3.1	3.6	5.9								
	350	0.7	0.5																

**Table 8.** Results of compressive strength ( $f_c$ ) tests for specimens made with cohesive soil after 28 days of curing [MPa]

w/c		4.4	4.2	4.0	3.8	3.6	3.4	3.2	3.0	2.8	2.6	2.4	2.2	2.0	1.8	1.6
V <sub>z</sub> [dm <sup>3</sup> /m <sup>3</sup> ]	800								1.1	1.3	1.5	1.9	2.1	2.8	3.2	4.3
	750	0.7	0.6	0.9	0.9	0.9	1.1	1.2	1.3	1.5	1.7	1.7	2.3	3.5	3.7	
	700	0.8	0.9	0.8	0.7	1.0	1.1	1.2	1.2	1.4	2.5	2.2				
	650	1.1	0.6	1.0	1.2											



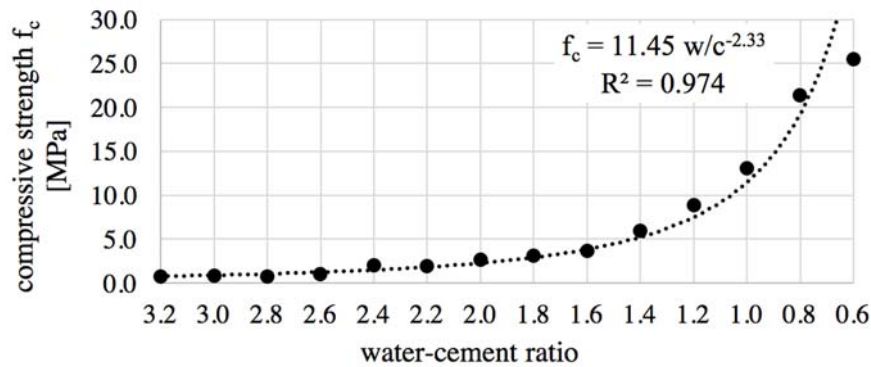
**Figure 3.** Compressive strength chart for specimens made with non-cohesive soil depending on the water-cement ratio and cement paste volume fraction after 28 days of curing



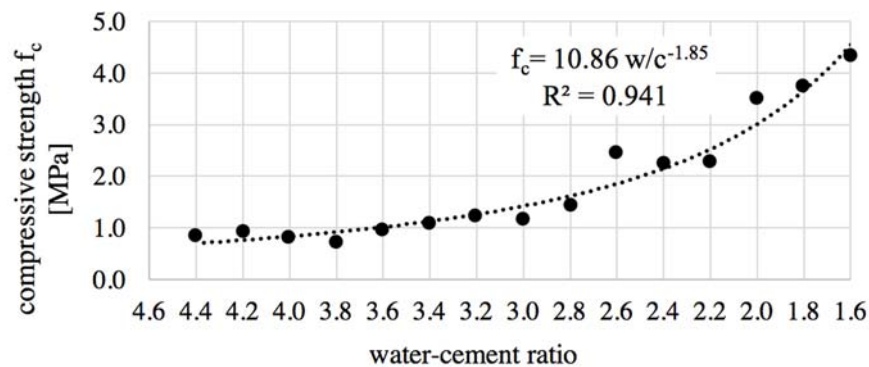
**Figure 4.** Compressive strength chart for specimens made with cohesive soil depending on the water-cement ratio and cement paste volume fraction after 28 days of curing

For compressive strength after 28 days, the range of results obtained ranged from 0.5 to 27.4 MPa for non-cohesive soil and from 0.6 to 4.3 MPa for cohesive soil. Analysing the effect of changes in cement paste content  $V_z$  and w/c ratio on the results obtained, it can be stated again that reducing both the cement paste content  $V_z$  and the w/c ratio results in an increase in the compressive strength of the composites tested for both types of soil.

In order to make the test results obtained useful for the practical design of soil-cement using both cohesive and non-cohesive soil, an attempt was made to determine the correlation between soil-cement composition and the properties of the composite obtained. The charts below (Figures 5 and 6) show the effect of w/c ratio on compressive strength after 28 days of curing. It has been observed that the power function matches the variation presented very well. The power functions determined reflect the results obtained very accurately as evidenced by very high values of determination coefficients, which range from 0.941 to 0.974.



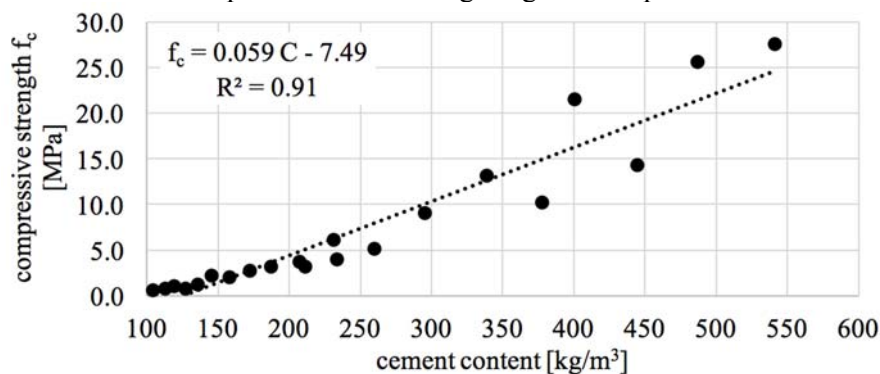
**Figure 5.** Compressive strength chart for specimens made with non-cohesive soil depending on the water-cement ratio after 28 days of curing



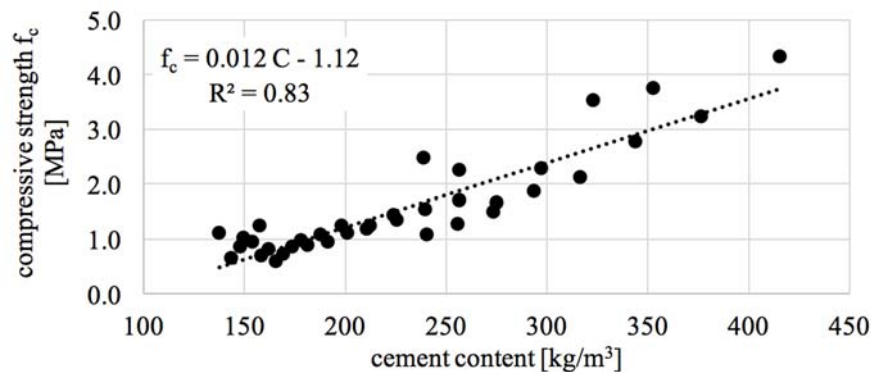
**Figure 6.** Compressive strength chart for specimens made with cohesive soil depending on the water-cement ratio after 28 days of curing

The analysis of the results obtained indicates a rapid increase in compressive strength in composites for which the w/c ratio is lower than 1.6 for loose soil and 2.8 for compact soil. It was also found that there was a linear relationship between the universal parameter of composition characteristics, i.e. the amount of cement, and material strength. This is because the amount of cement results from the w/c ratio adopted and the amount of paste. The impact of the amount of cement (as the sole factor) on compressive strength of the soil-cements tested is shown in Figures 7 and 8.

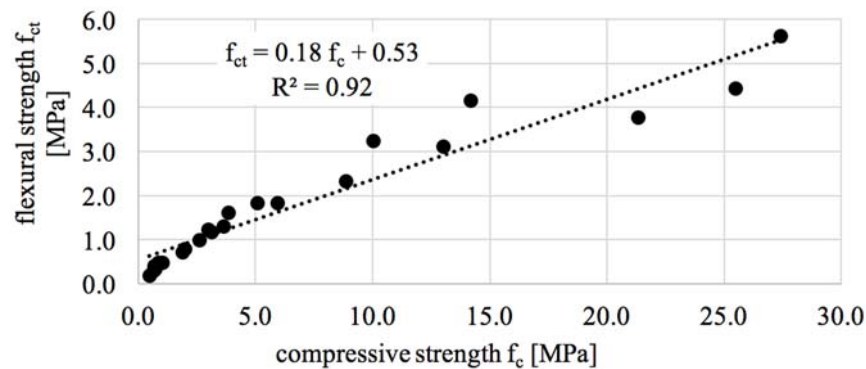
Moreover, flexural strength was compared to compressive strength (Figures 9 and 10) and it was observed that the proportion between these two values is around 0.18 for non-cohesive soil and around 0.24 for cohesive soil and is independent of the strength figures compared.



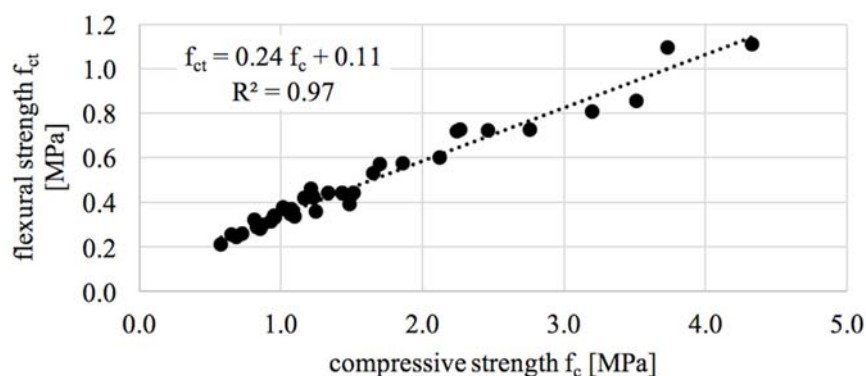
**Figure 7.** Impact of cement content on compressive strength for specimens made with non-cohesive soil after 28 days of curing



**Figure 8.** Impact of cement content on compressive strength for specimens made with cohesive soil after 28 days of curing



**Figure 9.** Comparison of flexural and compressive strength for specimens made with non-cohesive soil after 28 days of curing



**Figure 10.** Comparison of flexural and compressive strength for specimens made with cohesive soil after 28 days of curing

#### 4. Conclusions

The proper consistency of the soil-cement mix which enables its production by industrial methods is regulated by two factors, i.e. the amount and liquidity of cement paste. In the case of non-cohesive soil (medium sand), the demand for cement paste fluctuated from 350 to 500  $\text{dm}^3/\text{m}^3$  depending on the w/c ratio, and the w/c ratio varied from 3.2 to 0.6. For cohesive soil (loam), the demand for cement paste ranged from 650 to 800  $\text{dm}^3/\text{m}^3$ , and the w/c ratio ranged from 4.4 to 1.6.

With a proper amount of cement paste and an appropriate w/c ratio, it is possible to obtain a composite with a flexural strength in the range from 0.2 to 5.6 MPa for non-cohesive soil and from 0.2 MPa to 1.1 MPa for cohesive soil. For compressive strength, the range of results obtained ranged from 0.5 to 27.4 MPa for non-cohesive soil and from 0.6 to 4.3 MPa for cohesive soil.

The brittleness of the soil-cements analysed, expressed as the ratio of flexural strength to compressive strength in the case of composites made with non-cohesive soil is 18%, while for composites containing cohesive soil it is 24%.

The functions, both linear and power ones, accurately reflect the impact of the amount of cement and of the w/c ratio on the mechanical properties of soil-cement composites and thus provide practical tools for designing the compositions of these highly useful construction materials. While the applicability of the equations presented is unlimited owing to the range of consistencies of the concrete mixes used in practice, it should be stressed that the analytical results obtained should only be applied in quantitative terms to soil-cement composites produced using non-cohesive (medium sand) and cohesive (loam) soils reinforced with paste made using II/B-S 32.5R cement.

## References

- [1] M. Topolnicki, "Ground improvement with in-situ soil mixing method", "Wzmacnianie i uszczelnianie gruntu metodą mieszania in-situ (Soil Mixing)," *Inżynieria Morska i Geotech.*, vol. 6, pp. 385–398, 2003.
- [2] J. Madej, "Ground improvement", "Ulepszanie podłoża," *Materiały pomocnicze do wykładów z zakresu geotechniki, Politechnika Koszalińska*, 2015.
- [3] A. Leśniewska, "Strength and technological aspects of ground improvement with wet deep soil mixing method", "Wytrzymałościowe i technologiczne aspekty wzmacniania gruntu metodą wglębnego mieszania na mokro," *Rozprawa doktorska, Politechnika Gdańska*, 2007.
- [4] S. Topoliński, Testing the strength of organic soil-cement binder composites formed by mixing method", "Badanie wytrzymałości kompozytów grunt organiczny-spoivo cementowe formowanych metodą mieszania," *Rozprawa doktorska, Uniwersytet Technologiczno-Przyrodniczy im. Jana i Jędrzeja Śniadeckich w Bydgoszczy*, 2014.
- [5] PN-EN 1015-3: 2000 Methods of test for mortar for masonry - Part 3: Determination of consistence of fresh mortar (by flow table).
- [6] PN-EN 12390-5: 2011 Testing hardened concrete - Part 5: Flexural strength of test specimens.
- [7] PN-EN 12390-3: 2011 Testing hardened concrete - Part 3: Compressive strength of test specimens.