Oryginalny artykuł naukowy

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Concrete repair using two-stage concrete method

Zastosowanie metody dwuetapowego betonowania do naprawy betonu

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Streszczenie. W ciągu ostatnich dziesięcioleci technologia betonowania rozwinęła się w różnych kierunkach, m.in. ulepszając metody przygotowania i układania betonu w celu osiągnięcia wysokiej jakości przy utrzymaniu niskich kosztów. Metoda dwuetapowego betonowania polega na umieszczeniu grubego kruszywa w formie, a następnie wprowadzeniu zaprawy cementowej tak, aby wypełnić puste przestrzenie między cząstkami kruszywa. Ze względów ekonomicznych i technicznych beton otrzymany tą metodą jest stosowany przede wszystkim do budowy i naprawy konstrukcji masywnych, zwłaszcza fundamentów, konstrukcji podwodnych, a także we wszystkich rodzajach konstrukcji z gęsto rozmieszczonym zbrojeniem. W artykule przedstawiono wybrane realizacje, w których wykorzystano taki beton w pracach remontowych, a także wytyczne i wzory opisujące jego parametry mechaniczne: moduł sprężystości, wytrzymałość na rozciąganie i skurcz. Na podstawie badań stwierdzono, że moduł sprężystości oraz wytrzymałość na rozciąganie betonu otrzymanego metodą dwuetapowego betonowania są równe lub większe niż betonu zwykłego o tej samej wytrzymałości na ściskanie.

Słowa kluczowe: beton otrzymany metodą dwuetapowego betonowania, moduł sprężystości, wytrzymałość betonu na ściskanie i rozciąganie, skurcz.

Abstract. During the last decades the concrete industry has widely developed in many directions, e.g. improving the methods of pouring concrete in order to achieve high quality concrete and low cost. Two-stage concrete (TSC) is produced by placing coarse aggregate in a form and injecting a cement-sand grout in order to fill the voids between aggregate particles. For economic and technical reasons two-stage concrete is particularly used for construction and repair of massive structures, especially foundations, underwater constructions, and all kinds of construction with closely spaced reinforcement. The paper presents implementations of the two-stage technology in repair works, formulae and guidelines to assess the concrete mechanical parameters,e.g. modulus of elasticity, tensile strength and drying shrinkage. It was found that the modulus of elasticity and splitting tensile strength of two-stage concrete are equivalent or higher than the parameters of conventional concrete of the same compressive strength.

Keywords: two-stage concrete, modulus of elasticity, strength, splitting tensile, shrinkage.

Concrete is one of the most important materials for construction. Scientific studies and research programmes were focused on the development of technologies to improve distinct concrete parameters, improve economical cost at production stage or at long term (durability). A possible direction to improve the concrete technology is the concept of two-stage concrete (pre-placed aggregate concrete) or TSC. The TSC gets its name from the method used for concrete placement. Following this technique, first a formwork is constructed and the stone aggregate fraction is densely placed. The stone aggregate is washed and screened prior to placement in order to remove all fines. Grout is then injected through the forms to provide the matrix. The grouting starts from the bottom of TSC form. The formwork must be stronger and tighter than usually suitable for conventional concrete. The proper moulds minimize grout leakage and resist the lateral deformation that occurs as the grout is injected under pressure. In TSC no consolidation process, e. g. vibration is required. The TSC provides better durability than normal concrete (NC). In other words, the best method of any repair to accomplish damages is the use of TSC. First of all weak concrete parts are removed by chipping, usually to the depth behind the reinforcement. If the steel bars are rusted strongly, requiring replacement, the unsuitable sections are cut out and new pieces are spliced to the old bars, usually by welding. Next, the concrete is washed and coarse aggregate is placed behind the forms as they are erected. Finally, special grout is pumped into the aggregate beginning at the bottom. This grout used to make TSC should be highly fluid. Therefore, it penetrates intimately all of the minute indentations in the rough surface of the old concrete to establish perfect initial bond [1]. It is probable that the cost of TSC is less than of the conventional concrete by 20 – 40%, hence this cost reduction is reflected in the repair process [2].

Site applications. Typically, TSC is used in large repair projects, particularly where underwater concrete placement is required or when conventional placing of concrete would be difficult. Typical applications include underwater repair of stilling basins, dams, bridges, abutments and footings. The TSC has also been used to repair beams and columns in industrial plants [1]. For example, in Poland large-scale two-stage concreting was applied in two cases: laying the foundations for an 18-storey building in Gdańsk (Poland) (about 350 m^3), and the damage repair of a water dam in Czchow near Cracow (Poland) (about 400 m^3) underwater concreting, on the Dunajec River. In both cases sufficient technological and economical results were obtained [2].

Jackets and collars. In the process of jacketing a section of an existing structural member is restored to original dimensions or increased in size by encasement in new Portland cement or polymer-modified Portland cement concrete. A steel reinforcement cage is constructed around the damaged section to be filled with shotcrete or cast-in-place concrete [3]. Collars are jackets which surround only a part of a column or pier, typically used to provide an increased support to the slab or beam at the top of the column. The form for the jacket

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may be temporary or permanent, it may consist of timber, corrugated metal, pre-cast concrete, rubber, fiberglass or special fabric, in dependence of the purpose and exposure. The jacket form is placed around the section to be repaired, creating an annular void between the jacket and the surface of the existing member. The form should be provided with spacers to assure equal clearance between the existing member. A variety of materials including conventional concrete and mortar, epoxy mortar, grout, and latex modified mortar and concrete have been used as encasement materials [3].

Objective of the study

The paper presents the application of the two-stage concrete method in conventional construction, especially in the patch repairs of deteriorated concrete. It is necessary to say that an important point in the patch repair technique is to replace deteriorated concrete with a suitable material of excellent mechanical properties in order to avoid similar defects in the same portions at a long term in the future.

Experimental results

As mentioned before, the study is a result of analysis of a great amount of experimental data in order to obtain a better understanding of the behaviour of TSC as a supplementary method instead of applying normal concrete (NC) for the production of structural and repair material. Therefore, the following properties of TSC are presented.

Tensile strength of TSC. The **split tensile** strength of TSC was investigated in a 28 day period [4]. The obtained data are presented in Table 1. Splitting tensile tests were conducted on three specimens of each concrete type at 28 days according to the procedures outlined in ASTM C 496. The splitting tensile strength f_s is calculated using the following equation

$$f_s = 2P/\pi LD \text{ [MPa]} \qquad (1)$$

where:

P – maximum applied load [kN];
L – specimen length [mm];
D – specimen diameter [mm].

The actual values of tensile strength at w/c ratios of 0,40 and 0,45 measured from 3,1 MPa to 3,3 MPa, which indicate satisfactory results, especially considering a minimum cost of concreting and using no vibration tools. Furthermore, excellent results can be expected even using a high w/c ratio of 0,55, where the mean tensile strength is nearly 2,5 MPa.

Table 1. Mean splitting tensile strength of two-stage concrete at 28 day.
Tabela 1. Wytrzymałość średnia na rozciąganie przy rozłupywaniu betonu dwuetapowego po 28 dniach

Water to Cement Ratio (W/C)	Cement to Sand Ratio (C/S)	Split Tensile (lab.) [MPa]	Split Tensile (theoretical) [MPa]
0,40	2:1	3,35	3,37
0,45		3,14	3,16
0,50		2,83	3,01
0,55		2,27	2,81
0,40	1:1	3,34	3,13
0,45		3,02	2,90
0,50		2,86	2,70
0,55		2,53	2,60

The test method to measure tensile strength of concrete is an indirect tension test. In this test method compressive load is applied to a concrete cylinder along its axis by means of two steel punches placed on the top and bottom surfaces of the cylinder [4]. Typical crack of a specimen occurs after **double-punch** failure. Most of the cylinder specimens failed into three equal parts. This type of failure was almost identical to that given in [5] for ordinary concrete. The double-punch tensile strength test results obtained for TSC are presented in Table 2.

The unconfined **compressive strength** of two-stage concrete was measured in a 28 day period. Figure 1 shows the mean and individual strength values for three specimens per w/c ratio in a 28 day time. It can be seen that the mean compressive strength equal 31,9 MPa is attainable at 28 days with the w/c ratio equal to 0,45. Figure 1 demonstrates strength reduction due to the w/c ratio increase. Although there is some variation in strength measured per w/c ratio, the strength reduction is approximately linear. This observation is consistent with the unconfined compressive strength measurements of two-stage concrete cube specimens (300 x 300 x 300 mm) [6].

Table 2. Mean double-punch tensile strength of two-stage concrete at 28 day
Tabela 2. Wytrzymałość średnia betonu na rozciąganie przy próbie dwustronnego przebicia dla betonu dwuetapowego po 28 dniach

Water to Cement Ratio (W/C)	Cement to Sand Ratio (C/S)	Double-Punch (lab.) [MPa]	Double-Punch (theoretical) [MPa]
0,40	2:1	2,38	2,29
0,45		1,81	2,11
0,50		1,78	2,00
0,55		1,73	1,83
0,40	1:1	2,36	2,09
0,45		2,09	1,90
0,50		2,05	1,74
0,55		1,49	1,66

$$\bar{f}_c = 62{,}08 - 71{,}99(w/c) + 0{,}52(c/s) \qquad (2)$$

The equation 2 is illustrated in Figure 1 for a c/s ratio equal 1,0. It is observed to under-predict the strength of the tested cylindrical specimens. The predicted mean strength from Equation 2 varies from 87% to 93% of the measured mean strength. Decrement of the multiplicative factor on the w/c ratio in Equation 2 to account for cylindrical specimens yields the following relationship

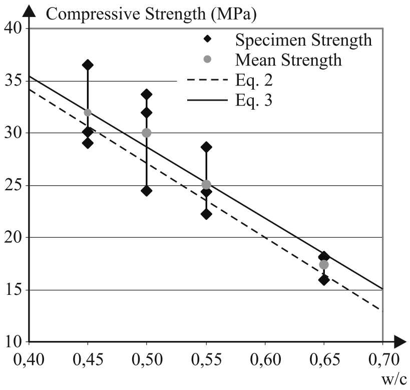

Fig. 1. Compressive strength vs. water-cement ratio.
Rys. 1. Relacja pomiędzy wytrzymałością na ściskanie a wskaźnikiem w/c

$$\bar{f}_c = 62{,}08 - 68{,}00(w/c) + 0{,}52(c/s) \qquad (3)$$

The case of c/s = 1,0 for specimens is investigated only. Further research is required to determine the suitability of Equation 3 for a range of c/s ratios. Another significant conclusion from the compressive strength data was a some what limited rate of strength development. This can be partly explained by

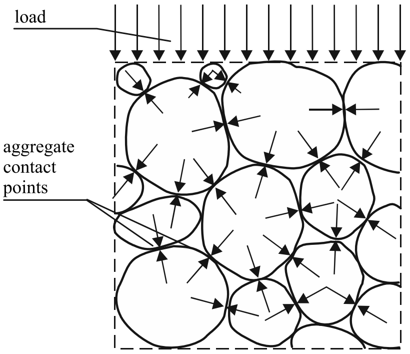

Fig. 2. Aggregate contact points in two-stage concrete
Rys. 2. Punkty kontaktowe pomiędzy kruszywem w betonie dwuetapowym

the fact that neither fly ash nor other pozzolans were incorporated in the cement grout. Although the mechanism of stress transfer is believed to be different from conventional concrete, the observations show that the coarse aggregate strength is a controlling factor for the strength of two-stage concrete. The observation suggests that the compressive strength of two-stage concretecan be conservatively estimated as half of its mortar strength. If this ratio can be substantiated with more mixtures and other sources of coarse aggregate, this simple rule-of-thumb can be adopted in the designof two-stage concrete.

The TSC differs from conventional concrete by a higher percentage of coarse aggregate [7]. Because of the point-to-point contact of the coarse aggregate Figure 2, **drying shrinkage of TSC** is about half of the conventional concrete. Since the aggregate is pre-placed and the grout is pumped under pressure, segregation is not a problem and virtually all substrate voids are filled with mortar. These factors make TSC an ideal material for the conditions where considerable congestion of reinforcement or other embedment, or difficult access exists. Ability of the grout to displace water from the voids between aggregate particles during injection makes this material particularly suitable for underwater repairs [2]. Since most repairs are made on older Portland cement concrete not undergoing further significant shrinkage, the repair material must also be essentially shrinkage-free or able to shrink without losing bond. Shrinkage of cementitious repair materials can be reduced by using mixtures with very low water-cement ratios or using construction procedures that minimize the shrinkage potential.

Drying shrinkage of normal concrete (NC) is caused by physical-chemical properties of the cement paste. In TSC the grout fills only the cavities, thus the basic mass of concrete is the stone skeleton only. Drying shrinkage practically occurs in the vicinity of cavities. Under ordinary conditions and proper curing, the lower drying shrinkage of TSC is attributed to the high content of stone aggregate and the grain-to-grain contact as stated above. A lower drying shrinkage may result in the reduced cracking repair overlays.

The TSC shows good volume stability and low calorific value, highly important in massive structures. Some results for drying shrinkage of NC and TSC are presented in Table 3. Small values of contraction may be explained by continuity of a skeleton, where the individual grains of stone filling are in close contact with one another, which results in their small negative deformation.

Table 3. Drying shrinkage of two-stage concrete and normal concrete

Tabela 3. Skurcz betonu dwuetapowego i betonu zwykłego

Age (days)	Type of Concrete	Shrinkage (-) 10^{-5}	Temperature in Mass Concrete + °C
7	NC	5	38
	TSC	2,5	20
28	NC	2,5	32
	TSC	8	25
56	NC	-2	23
	TSC	17	18
80	NC	-8	17
	TSC	8	15
100	NC	-15	15
	TSC	2,5	15

The experimental data analysis and the statically obtained relations allow to formulate the relationship between the modulus of elasticity and the compressive strength of TSC, where the compressive strength is calculated as follows

$$\overline{f}_c = \beta_0 + \beta_1 + \overline{\overline{f}_g^{\beta_2}} \text{ (MPa)} \qquad (4)$$

where:

$\overline{f}_c$ – compressive strength of TSC;

f_g – compressive strength of grout;

β_0, β_1 and β_2 – constants assumed for the specific aggregate [6].

The **modulus of elasticity of the TSC** is mainly affected by physical properties of the stone aggregate. The influence of the content of grout in the concrete is rather meaningless. It has been observed that the factors affecting the compressive strength act upon the elastic modulus of TSC too, see Figure 1. The initial tangent modulus of elasticity of TSC determined as a function of strains can be calculated by the following equation:

$$E_{tsc}(\varepsilon_1) = d\sigma'/d\varepsilon_1 = 3 \cdot a(\omega, \varsigma) \cdot \varepsilon_1^2 + 2b(\omega, \varsigma) \cdot \varepsilon_1 + c(\omega, \varsigma) \text{ (GPa)} \qquad (5)$$

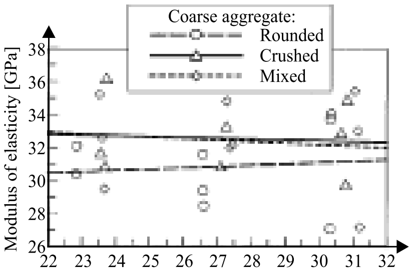

Fig. 3. Relationships between modulus of elasticity of two-stage concrete and its compressive strength

Rys. 3. Związek pomiędzy modułem sprężystości oraz wytrzymałością na ściskanie betonu dwuetapowego

where:

a, b and c – regression coefficients [8];

ω, ς – coefficients depending on water-cement and cement-sand ratios [8].

For initial tangent modulus of elasticity it is assumed that $\varepsilon_1 = 0$. The tangent elastic modulus is obtained from the analysis of the stress-strain curves for each type of stone aggregate and the mix proportions [9].

Conclusions

The following conclusions can be formulated.

- ■ TSC is very efficient material for the repair of deteriorated concrete elements.
- ■ Drying shrinkage of TSC is lower than that of NC; shrinkage is reduced due to the point-to-point contact of the stone aggregate particles.
- ■ The modulus of elasticity as a function of compressive strength of the TSC is investigated. The modulus values for specific types of aggregate can be described by linear constant functions.

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