Structural improvement in quality standards for shotcrete for primary lining in tunnel by Destructive & Non- destructive test methods

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ABSTRACT
In this paper, presentation is given of introduction of shotcrete history in tunneling as well as destructive and non-destructive test methods for evaluating the shotcrete strength and quality of a tunnel primary lining. The relation between shotcrete properties (compressive strength, flexural strength modulus of elasticity, and homogeneity) measured across the tunnel profile and along the whole tunnel by applying the destructive and non-destructive methods. In destructive test methods are involving testing of compressive strength, flexural strength as per relevant standards. The non-destructive methods included an ultrasonic pulse velocity method and a hammer test.

The main purpose of this is the development of a method that evaluates the quality of shotcrete in underground structures during and after the construction work. Through the application of non-destructive and destructive test methods it is possible to assess the state of a tunnel in order to improve construction work. This will result in the higher quality of the tunnel lining and durability of the tunnel as a whole and cut remediation and maintenance costs.

Keywords
Shotcrete, Steel fibers, compressive strength, flexural strength homogeneity, modulus of elasticity, non-destructive and destructive test methods.

1. INTRODUCTION
The use of Shotcrete for the support of underground excavation was pioneered by the civil engineering industry. Reviews of the development of shotcrete technology have been presented by Rose (1985), Morgan (1993) and Frazěn (1992). Rabcewicz was largely responsible for the introduction of the use shotcrete for tunnel primary support in 1930's, and for the development of the New Austrian Tunneling Method for excavating in weak ground.

In recent years the hydro power as well as motor & railway tunnel industry has become major user of shotcrete for underground support. The simultaneous working of multiple headings, difficulty of access and unusual loading conditions are some of the problems which are peculiar to tunneling and which require new and innovative applications of shotcrete technogy.

Rehabilitation of conventional rockbolt and mesh support can be very disruptive and expensive. Increasing number of these excavations is being shotcreted immediately after excavation. The incorporation of steel fiber reinforcement into the shotcrete is an important factor in this escalating use, since it minimizes the labour intensive process of mesh installation.

Trials and observations suggest that shotcrete can provide effective support in mild rock burst conditions. While results from paststudies are still too limited to permit definite conclusions to be drawn, hence the quality of shotcrete is an important factor for primary supports in underground tunneling. The indications are encouraging enough that more serious attention will probably be paid to this application in the future.

In order to assess the current state of the said tunnels, among other tests, in-place test methods were employed in order to estimate the quality of the concrete used for the tunnel primary lining. [1] The said methods, which were aimed at the determination of concrete quality, involved visual inspection of the tunnels as well as non-destructive and destructive methods for testing the primary concrete lining.

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2. SHOTCRETE TECHNOLOGY
Shotcrete is a generic name for cement, sand and fine aggregate concretes which are applied pneumatically and compacted dynamically under high velocity.

2.1 Dry mix shotcrete
As illustrated in fig 1, the dry shotcrete components, which may be slightly dampened to reduce dust, are fed into hopper with continuous agitation. Compressed air introduced through a rotating barrel or feed bowl to convey the materials in a continuous stream through the delivery hose. Water is added to the mix at nozzle. Gunite, a proprietary name for dry sprayed mortar used in the early 1900's, has fallen into disuse in favour of the more general term shotcrete.

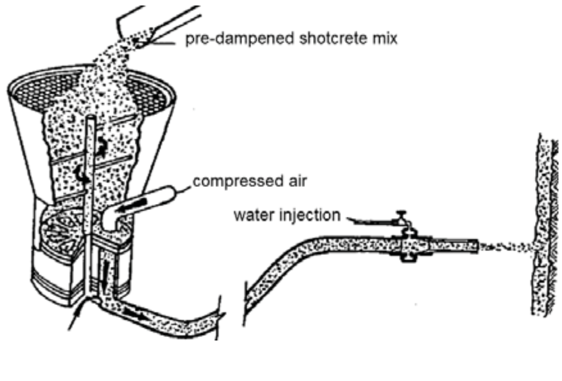

Fig 1: Simplified sketch of a typical dry mix shotcrete system.

2.2 Wet mix shotcrete

In this case the shotcrete components and the water are mixed (usually in atruck mounted mixer) before delivery into a positive displacement pumping unit, which then delivers the mix hydraulically to the nozzle where air is added to project the material onto the rock surface.As illustrated in fig 2.

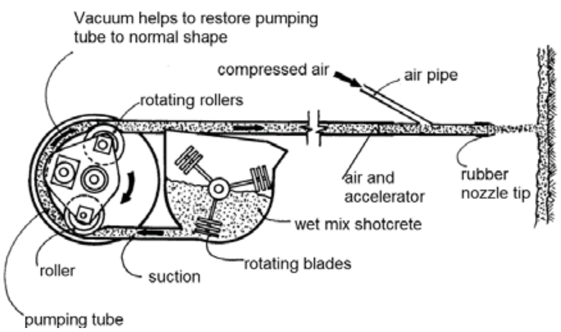

Fig 2: One typical type of wet mix shotcrete machine.

The final product of either the dry or wet shotcrete is very similar. The dry mix system tends to be more widely used in mining, because of inaccessibility for large transit mix trucks and it generally uses smaller and more compact equipment. The wet mix system is ideal for high production application in long tunnel, where access allows the application equipment and delivery trucks to operate on a more or less continuous basis. Decisions to use the dry or wet mix shotcrete process are usually made on site-by-site basis.

3. DESIGN OF SHOTCRETE SUPPORT

The design of shotcrete support for underground excavation is very imprecise process. However, one observation, which is commonly made by practical engineers with years of experience in using shotcrete underground, is that it almost always performs better than anticipated. It is only in recent years, with the development of powerful numerical tools, that it has been possible to contemplate realistic analysis, which will explore the possible support-interaction behavior of shotcrete. It is also important to recognize that shotcrete is very seldom used alone and its use in combination with rockbolts, cablebolts, lattice girders or steel ribs further complicates the problem of analyzing its contribution to support.

Current shotcrete support "design" methodology relies very heavily upon rules of thumb and precedent experience. Wickham et al (1972) related the thickness of a shotcrete tunnel lining to their Rock Structure Rating (RSR). Bieniawski (1989) gave recommendations on shotcrete thickness (in conjunction with rockbolts or steel sets) for different Rock Mass Ratings (RMR) for a 10 m span opening. Grimstad and Barton (1993) have published updated relating different support systems, including shotcrete and fiber reinforced shotcrete, to the Tunneling Quality index Q. Vandewalle (1993) collected various rules of thumb from variety of source and included them in his monograph.

4. Constituent materials for shotcrete

4.1 Cements

Cement shall comply with the requirements of alternatively with the national standards or regulations valid in the place of use of the sprayed concrete. Only cement with established suitability for sprayed concrete applications shall be used. The cement content should normally be between 350 and 450 kg/m^3 of concrete for dry process and between 400 and 500 kg/m^3 of concrete for wet spraying process.

4.2 Aggregates and mixing water

Aggregates and water shall comply with the requirement of national standards and regulations valid in the place of use of shotcrete. For sprayed concrete the quality of aggregate is most importance, in relation to performance of both the fresh and the hardened concrete.

4.3 Steel reinforcement

Steel reinforcement is used to increase the flexural strength and reduce cracks. Steel reinforcement is in the form of fabric and its use is recommended for thick layers (≥ 50mm). for most uses, reinforcing steel fabric with a mesh of 100 mm to 150 mm and a wire diameter of no more than 10 mm is widly accepted. Steel reinforcement complies with relevant national standards or regulations valid in the place of use of sprayed concrete.

4.4 Steel Fibers

Fibers are generally used to increase the toughness of the concrete and to reduce or control the cracking. Fibers are normally supplied collated with fast-acting ater-soluble glue, or as uncollated individual fibers.

Of the many developments in the shotcrete technology in recent years steel fibers are introduced in shotcrete. Steel fiber shotcrete was introduced in 1970's and since gained world-wide acceptance as a replacement for the traditional wire mesh reinforced shotcrete. The main role that reinforcement plays in shotcrete is to import ductility to an otherwise brittle material. As pointed out earlier, rock support is only called upon to carry significant loads once the rock surrounding an underground excavation deforms. This means that unevenly distributed non-elastic deformations of significant magnitude may be overload and lead to failure of of the support system, unless that system has sufficient ductility to accommodate these deformations. The addition of steel fibers to shotcrete enhances both flexural and compressive strength of hardened shotcrete by up to 20%.

Steel fibers are straight or deformed cold drawn steel wires, straight or cut sheet fibers, fibers milled from steel blocks or melt extracted fibers which can be homogeneously mixed into concrete and mortar. Steel fibers are divided into five main groups and are defined in accordance with the basic material used for the production of the fibers.

Group I Cold drawn steel wire
Group II Cut steel fibers

Group III Milled from steel blocks
Group IV Melt extracted fibers
Group V other steel fibers

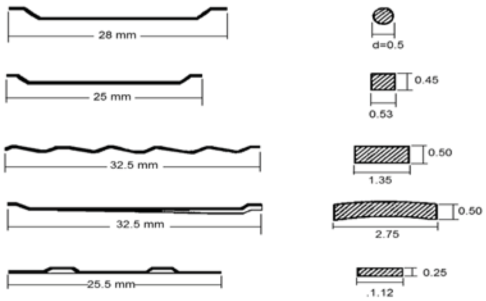

Fig 3: Steel fibers types available in the market

(Note: all dimensions are in mm)

4.5 Admixtures

A sprayed concrete mix may include admixtures such as plasticizers, retarders, etc., (just as conventional concrete does to improve the fresh mix properties and the hardened concrete quality), to ensure a good spraying application and to meet early strength requirements. The designation 'chloride-free' for admixtures implies that the chloride ion content does not exceed 0.1% by mass of the admixture.

Plasticizers are used in % dosages to achieve pumpable concretes with minimum water content and to improve quality of shotcrete.

Superplasticizers are used in sprayed concrete to minimize the amount of water in the mix, thereby improving the final quality. They are mainly used to give the required consistence for spraying and to aid pumpability.

Accelerators are added to concrete during spraying to increase the stiffening rate, to produce a fast set and to get sufficient early strength development. A fast setting concrete may be necessary to build up the lining at the required thickness and to ensure overhead security. The dosage should be adjusted to ensure good cohesion between individual passes producing a single layer.

Bond improvers - internal curing admixtures are special admixtures added to the basic mix of the sprayed concrete or at the nozzle to improve the bond between the sprayed concrete layers and/or adhesion to the substrate surface of the sprayed concrete.

Additives

Pulverized fuel ash (Fly ash): the source of the fly ash should be selected with care to ensure that the free alkali level is not excessive.

Ground granulated blast furnace slag (GGBS): minimum value of the specific surface (Blaine) should be 450±25 m2/kg.

Silica fume: can be added as a powder or as slurry. The normal level of addition is 3 - 8% (by dry mass of the Portland cement) unless otherwise directed by the client or his representative. Higher levels may require additional precautions to minimize shrinkage.

The following additional requirements should be met:

- Content of amorphous SiO_2 ≥ 85% (by mass)
- MgO ≤ 5%
- Ignition loss ≤ 4%
- Specific surface (BET) > 2.104 m2/kg

5. MIX DESIGN OF SHOTCRETE

Typical steel fiber reinforced silica fume shotcrete mix designs are summarized in Table 1. These mixes can be used as a starting point when embarking on the shotcrete program, but it may be necessary to seek expert assistance to "fine tune" the mix design to suit site specific requirements. For many dry mix applications it may be advantageous to purchase premixed shotcrete bags of up to 1500 kg capacity, as illustrated in fig 4.

Table 1. Typical steel fiber reinforced silica fume shotcrete mix design.

Components	Dry mix		Wet mix	
	kg/m^3	% dry materials	kg/m^3	% wet material
Cement	420	19.0	420	18.1
Silica fume additive	50	2.2	40	1.7
Blended aggregate	1670	75.5	1600	68.9
Steel fibers	60	2.7	60	2.6
Accelerator	13	0.6	13	0.6
Superplasticizer	-	-	6 liters	0.3
Water reducer	-	-	2 liters	0.1
Water	Controlled at nozzle	-	180	7.7
Total	2213	100	2321	100

Fig 4: Bagged pre-mix dry shotcrete components being feed to hopper of shotcrete machine.

5.1 Shotcrete application

The quality of the final shotcrete product is closely related to the application procedure used. These procedures includes: surface preparation, nuzzling technique, lightening, ventilation, communications, and crew training.

Shotecrete should not be applied directly to a dry , dusty or frozen rock surfaces. The work area is usually sprayed with an air-water jet to remove loose rock and dust from the surface to be shot. The damp rock will create a good surface on which to bond the initial layer of shotcrete paste. The nozzleman commonly starts low on the wall and moves the nozzle in small circles working his way up towards the back, or roof. Care must be taken to avoid applying fresh materials on top of rebound or over sprayed shotcrete. It is essential that the air supply is consistent and has sufficient capacity to ensure the delivery of a steady stream of high velocity shotcrete to the rock face. Shooting distances are ideally about 1 to 1.5 meters. Holding the nozzle further from the rock face will result in a lower velocity flow of materials which leads to poor compaction and higher portion of rebound.

A well trained operator can produce excellent quality shotcrete manually, when the work area is well-lit and well-ventilated, and when the crews are in good communication with each other using prescribed hand signals or voice activated FM radio handsets. However, this is a very tiring and uncomfortable job, especially for overhead shooting, and compact robotic systems are increasingly being used to permit the operator to control the nozzle remotely.

Fig 5: A truck mounted shotcrete robot

Fig 6: Compact trailer-mounted robot

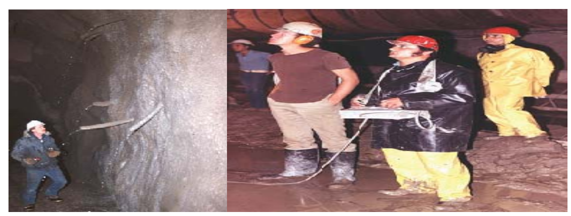

Fig 7: Shotcrete operated using a remotely controlled unit to apply shotcrete to rock face and Plastic pipes used to provide drainage for a shotcrete layer applied to rock mass with water-bearing joints.

When shotcrete is applied to rock masses with well-defined water-bearing joints, it is important to provide drainage through the shotcrete layer in order to relative high water pressures. Drain holes fitted with the plastic pipes as illustrated in fig 6, are commonly used for this purpose.

6. Evaluation of quality of shotcrete by applying different test methods on shotcrete

As per the Marijan Skazlic, Irina Stipanovic and Josko Krolo, Faculty of Civil Engineering Zagreb, Croatia, The research was conducted in the tunnels that are under construction on the Zagreb - Rijeka highway in Croatia. Testing was carried out on site and in a laboratory on specimens taken from the tunnels. The non-destructive methods included an ultrasonic pulse velocity method and a hammer test.

In order to assess the state of the built tunnel structure, the quality of concrete of the tunnel primary support will be tested after it had been constructed by using the combination of the destructive and non-destructive methods according to the relevant national Standard. The test methods employed will be the following:

- Non-destructive methods (testing of compressive strength of concrete by using a hammer test method), and
- Destructive methods (determination of concrete compressive strength and modulus of elasticity on drilling cores taken out of the structure, testing of concrete strength and homogeneity on drilling cores taken out of the structure by using an ultrasonic pulse velocity method).

Besides the above-mentioned test methods, the dimensions of the built primary concrete lining will be measured and visual inspection of the whole tunnel will be made.

Testing by the non-destructive test methods will be done on representative profiles along the tunnel spaced about 25 metres apart. In each profile there were 4 to 5 measuring points at the tunnel sides and the cap. The destructive tests will be performed, i.e. the drilling cores will be taken out of the tunnel primary lining at about each 50 metres of the tunnel length at the same measuring points at which the non-destructive testing of strength will be carried out by means of a test hammer. The representative profiles for testing will be selected based on visual inspection of the tunnel and the condition that there was at least one profile in each particular category of the rock mass along the tunnel.

The non-destructive test method involving the use of digital test hammer will be employed to determine the surface strength of shotcrete of the tunnel primary lining on the basis of a rebound value. As the hammer test will be carried out on shotcrete placed in the tunnel structure, prior to this testing each measuring point had to be prepared in the manner as to have ground, clean and dry surface, which is a very complex and hard work. The number of impacts by the test hammer on each individual measuring point will be 30. The hammer tests are being carried out at 198 measuring points along the tunnel. By comparing these results with those of the destructive testing on drilling cores it will possible to estimate the strength and homogeneity of concrete in the tunnel primary support. Since the age of the tested concrete did not exceed one year, it is safe to say that the influence of carbonisation on the obtained test results was negligible.

The drilling cores will be taken out of the structure by means of a drilling machine with diamond crown of 95-mm diameter. The cores were prepared for testing and then hammer tested to obtain average correction factor between the core compressive strength and mean compressive strength obtained by non-destructive tests performed by using the test hammer in the tunnel. After that compressive strength of the drilling cores is determined according to established standard procedures. Since the cores taken out of the structure will be of various lengths their compressive strength will be calculated as for a cube of 200-mm side according to BS 1881 (Part 120, 1983) or IS 516. A total number of drilling cores taken out of the structure will be 112.

Each profile of the tunnel in which the destructive tests on one of the samples will be performed will be also tested by using an ultrasonic pulse velocity test method. This is a non-destructive test method involving the measuring of the time required for the impulse of longitudinal oscillations to be sent from the probe of a transmitter to that of a receiver. By using this method it is possible to determine a number of different concrete properties, and for this research the most important ones are concrete homogeneity (uniformity) and the strength of concrete within the structure.

6.1 Analysis of the results

In the case when a modulus of elasticity is not determined experimentally, the relevant national Regulations on Concrete and Reinforced Concrete Structures specify that the modulus of elasticity may be determined based on the known compressive strength of concrete according to the following empirical formula:

$$E_{c,s} = 9.25 \cdot \sqrt[3]{f_c + 10} \quad (\text{GPa})$$

This formula was verified on the basis of the values of the modulus of elasticity and compressive strength determined for the drilling cores, and the results obtained are presented in the graph drawn in Figure 7. It is evident from the graph that the values of modulus of elasticity obtained experimentally and the values of those calculated from the known value of compressive strength by using the above-mentioned empirical formula do not match. Namely, the modulus of elasticity of the tested shotcrete obtained experimentally are in average 20 % lower than those obtained empirically. Such a result can be partially explained by the differences in the composition of shotcrete and plain concrete.

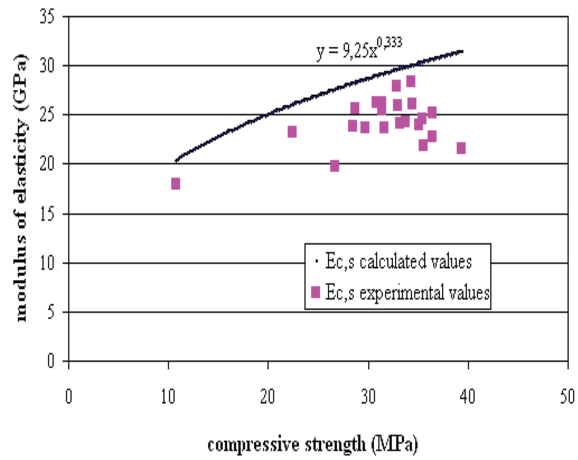

Fig 8: Relation between compressive strength and modulus of elasticity (theoretical and experimental values).

The measurements of ultrasonic pulse velocity obtained on the drilling cores taken out of the tunnel structure can be used to calculate dynamic modulus of elasticity of concrete. The dynamic modulus of elasticity depends on the ultrasonic pulse velocity (v), concrete density (ρ) and Poisson's coefficient (μ) according to the following formula:

$$E_{c,d} = \frac{v^2 \cdot \rho \cdot (1+\mu) \cdot (1-2\cdot\mu)}{1-\mu} \quad (\text{GPa})$$

Figure 8 shows the dependence of the ratio between static and dynamic modulus of elasticity on concrete compressive strength. The obtained values of the dynamic modulus of elasticity of concrete are, on average, about 50% higher than the values of the static modulus of elasticity calculated experimentally. The values of the dynamic modulus of elasticity of shotcrete that were obtained are higher in average by about 50 % than the static modulus of elasticity calculated experimentally.

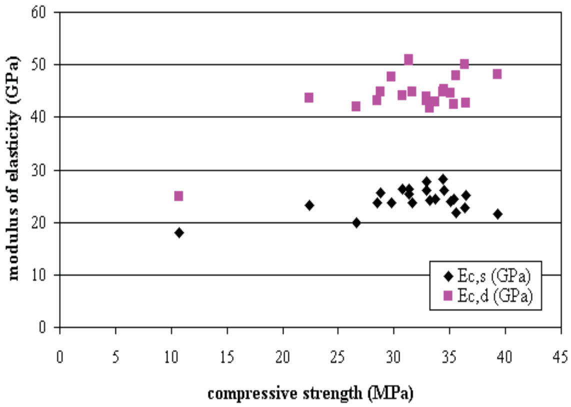

Fig 9: Correlation between compressive strength and modulus of elasticity (static and dynamic).

The diagrams in Figures 9 and 10 show average values of compressive strength at the sides and cap along the tunnel obtained by using the hammer test method in the tunnel, by using the same method on the drilling cores, and by determining compressive strength on the drilling cores.

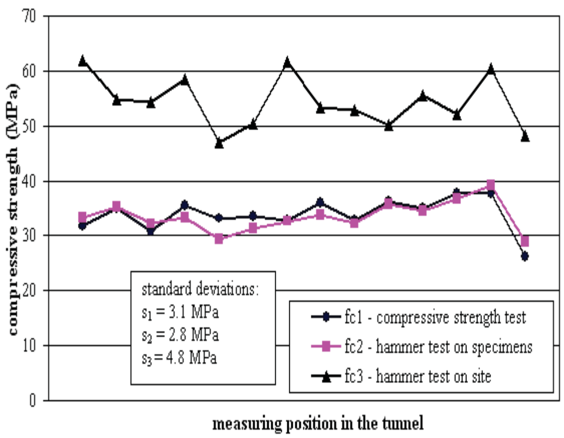

Fig 10: Comparison of destructive and non-destructive testing of compressive strength, performed on specimens and on-site (position - sides of the tunnel).

Figure 9 and Figure 10 shows that the use of the hammer test method along the tunnel primary lining gave significantly higher values and higher standard deviations than the use of the same method along the drilling cores taken out of the structure. The analysis of the same values obtained for the tunnel profile demonstrated that the differences in values are larger at the tunnel cap than at the tunnel sides, which is explained by more difficult working conditions when shotcrete is placed above head, i.e. at the tunnel cap. Based on the comparison of the values of compressive strength obtained by hammer testing and that of the drilling cores it is safe to conclude that the values obtained by hammer testing on the drilling cores correspond roughly to the real compressive strength of the tunnel primary support. Consequently, when estimating concrete quality after tunnel construction has been completed, it is necessary to use not only the non-destructive test methods (a test hammer) but also the destructive test method (drilling cores) to obtain the reliable values of compressive strength.

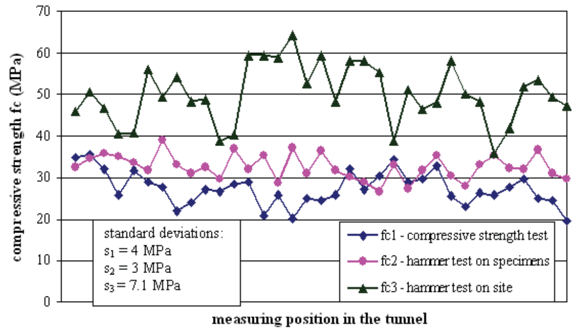

Fig 11: Comparison of destructive and non-destructive testing of compressive strength, performed on specimens and on-site (position - tunnel cap).

In conclusion, only the use of the non-destructive and destructive test methods for determining the quality of concrete makes it possible to estimate the quality of the built structure in a practical manner and with sufficient accuracy.

7. CONCLUSION

As the shotcrete is mixed with steel fiber, pozzolans, silica fume and additives etc., the disadvantages of conventional shotcrete are greatly improved, thus enabling shotcrete mixed materials to undertake a role of more versatile and multi-functional applications. The conclusions of the achievements that the application of steel fiber reinforced shotcrete having been obtained in world today will be enumerated as follows:

(1) The properties of SFRC/S in tensile strength, flexural strength, impact resistance, fatigue resistance, and creep resistance are proved to be more superior than those of conventional shotcrete.

(2) After being mixed with steel fiber, such disadvantages of concrete/shotcrete as brittleness is improved and ductility is increased. Meantime, the chance of the creation.

The tests carried out to estimate the quality of the tunnel primary support after the tunnel construction has been completed involved the non-destructive (the hammer test and ultrasonic pulse velocity methods) and destructive (the drilling cores taken out of the tunnel structure) test methods. On the basis of the results of the above tests, it can be concluded as follows:

- The modulus of elasticity of shotcrete determined experimentally are lower in average by 20 % than the same modulus determined by using compressive strength according to the empirical formula for plain concrete;
- The modulus of dynamic elasticity of shotcrete obtained by using the ultrasonic pulse velocity test method are higher by about 50% than the static modulus of elasticity determined experimentally;
- The values of surface compressive strength obtained by hammer testing in the tunnel demonstrate sharp departure from the compressive strength obtained on the drilling cores. This indicates that the combination of the destructive and non-destructive test methods should be used when estimating concrete quality after the construction has been completed.

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