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Izvorni znanstveni članak

TENSILE STRENGTH OF STEEL ROPES OF DIAMOND WIRE SAWS

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The efficiency of diamond wire saw upon exploitation of natural stone depends on the right choice of the constructional and technological factors of the machine, diamond wire and conditions, and way of exploitation in the particular kind of the rock. One of these parameters is the steel rope of diamond wire.

A long-standing work on testing and certifying of hoisting ropes, experience and knowledge acquired upon these testings, aroused us to a detailed analysis and testing of the ropes which are used in diamond wire shaping. The paper presents the results of testings of steel ropes of diamond wire and the testings of rope joints i.e. tensile strength which can resist the joints between separate rope sections. The suggested idea regarding construction desings of steel rope of diamond wire, which is used in natural carbonate stone exploitation, is based on this experimental testing of steel ropes.

Ključne riječi: Čelična užad, Dijamantna žica, Prirodni kamen

Učinkovitost dijamantne žične pile pri eksploataciji prirodnog kamena ovisi o pravilnom izboru konstrukcijskih i tehnoloških čimbenika stroja, dijamantne žice te uvjeta i načina eksploatacije u određenoj vrsti stijene. Jedan od tih parametara je i čelično uže dijamantne žice.

Dugogodišnji rad na ispitivanju i atestiranju izvozne užadi, iskustva i saznanja stečena pri tim ispitivanjima, ponukali su nas na detaljniju analizu i ispitivanja užadi koja se koriste pri formiranju dijamantnih žica. U radu su izloženi rezultati ispitivanja čeličnih užeta dijamantne žice i spojeva užeta, odnosno vlačnih sila koje mogu izdržati spojna mjesta između pojedinih sekcija užeta. Temeljem eksperimentalnih ispitivanja daje se prijedlog svrhovitijeg konstrukcijskog rješenja čeličnog užeta dijamantne žice, koja se koristi za eksploataciju prirodnog kamena karbonatnog sastava.

Introduction

A cutting element of a diamond wire saw is a diamond wire enclosed into the endless flow.

Note: *The term diamond wire comprises a completely shaped cutting tool, which consists of a steel rope with threaded diamond beads, springs, protecting and blocking spacers and joints. The term "diamond wire" itself is not totally correct, because the steel rope, as a part of this wire, consists of the wires. However, this term has been accepted in English and many other world languages (filo diamantato - Ital., dijamantna žica - Croat., fil diamante - French, hilo diamantado - Span.), so it is going to be used in the further text.*

The type and quality of the diamond wire, including the corresponding condition of the application in the particular rock type, have the crucial impact on the efficiency of the sawing. The correct choice of the construction and characteristics of diamond saw with the corrresponding condition of its application considerably influence its durability. The characteristics of diamond wire are determined by its construction as: type and shape of the beads, number of beads i.e. their pitch, type and number of springs, spacers of protective rings and joints. Steel rope is the core of diamond wire. Other wire elements are threaded on it, which together make up a cutting tool, which is the important part of this tool. Each breaking of the rope means direct loss of 3-5 beads. When the rope breaks there is a strike against the stone. Due to the fact that diamond beads do not stand dynamic strikes, in this moment a great number of beads is damaged, although this cannot be seen with the naked eye. Although they are very hard, diamonds are also very brittle and have, as all other crystals, planes of lower resistance. Therefore, diamond beads cannot stand higher impact loads.

Upon operation the rope is stressed by tension, bending, twisting and crushing. It is corroded by cooling water which is mixed with crushed stone particles and diamond beads and is under impact of internal forces due to its own hardness and brittelness. Therefore, the rope must have a high tensile strength, good elasticity, corrosion resistance and a relatively small mass.

Theoretical contemplations

The stresses, to which a steel rope of diamond wire is exposed during operation, do not depend on tensile stresses only but also on the stresses caused by bending of the rope on the driving wheel, positioning pulleys and the cut itself. They also depend on the stresses by the forces caused by friction resistance in the cut, wire bending due to streching of the thread line as well as on dynamic stresses upon normal transfer of force especially in exceptional cases. Resonance can also appear due to vibrations of diamond wire at the exit from the cut.

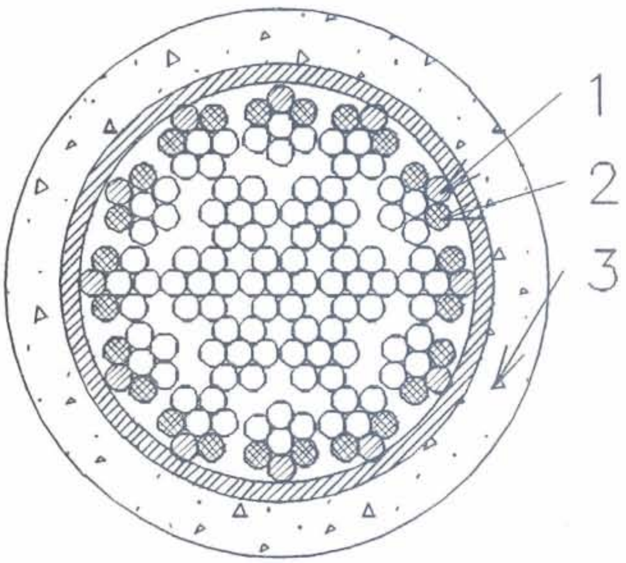

Fig. 1. Transmission of forces from a diamond bead to the rope, 1) Wires with complete footing, 2) Wires with partial footing, 3) Diamond bead

Sl. 1. Prijenos sila s dijamantne perle na uže, 1) žice s punim osloncem, 2) žice s djelomičnim osloncem, 3) dijamantna perla

Tensile stresses are consequence of static and dynamic forces which are in impact in the process of sawing by diamond wire. Upon each cycle of diamond wire, one part is in the cut and passes along its bended and rectilinear parts, while the other part is outside the cut and passes along the driving pulley and positioning pulleys. The rope is constantly stressed also on bending, which causes deterioration of material and breaking of wires. The rope is not in direct contact with these planes, so the forces are transferred to it via beads by means of surface wire layer in only one part of the circumference (Fig. 1). Thanks to the friction between the wires the force is transferred and distributed on the other wires of the rope. This also means that the wire contacts rub, deteriorate and decrease the metal crosssection. Upon bending of diamond wire in the cut (especially when the cut dimensions are small) of the driving pulley or pulleys, the surface wires of the rope must be lengthened (Fig. 2), which means again that the parts of one wire will move relatively in relation to the wire standing nearby, with which this wire is in contact (pointwise or linear). After passing over the curve the lengthened part of the rope is "coming back" and wires are again moving relatively in relation to one another, rubbing and deteriorating. The crossing of the wires in the specific strand or the crossing of surface wires in the nearby standing strands are especially unfavourable. Crushing appears on such a (pointwise) contact, which in combination with relative movement and rubbing causes intensive local deterioration i.e. decrease of the cross-section.

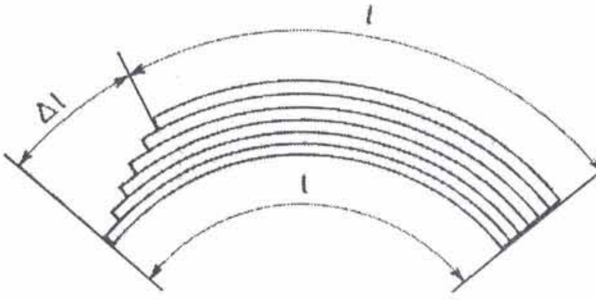

Fig. 2. Passing of the rope along the curvature
Sl. 2. Prijelaz užeta preko zakrivljenja

The elasticity of the rope must be extremely high, because the entire diamond wire must be extremely elastic. The hardness of the entire wire is increased by its shaping, i.e. putting of diamond beads, strings, rings and spacers. The elements which are threaded on the rope are free and are turning around the rope, which is facilitated by the bending of some rope parts upon operation, which requires torsion strength of the rope.

Experimental work

In the company Jadrankamen-Pučišća (the island of Brač) the consumption of different rope types was observed in order to determine the characteristics of diamond wire rope and changes of these characteristics after the operation within a certain period of time. The observed ropes were tested in the laboratory after samples were taken from the new ropes and the same ropes after particular ones had to be replaced due to deterioration. After a detailed visual examinations the testings of breaking strength, bending and twisting of the rope were also conducted. The results of these testings were presented at the 10th International Conference: Investigation, Production and Use of Steel Wire Ropes - Slowakia, 1998. (D u n d a , 1998).

The testings of the deteriorated ropes have pointed to the causes of decrease of tensile, torsion and bending strengths. The main cause of wire deterioration appeared to be corrosion, rubbing and crushing of the rope. These are also the places of the reduced wire resistance. It was determined that the wire joints are especially sensitive elements of diamond wire. The sudden changes of tensile strengths and the sudden repeated axial impacts, which appear upon the start-up of the saw after the break, have the highest effect on the links of the particular rope sections. These are therefore critical areas especially when the sawing angles are more acute. In order to find out if there is and how much is the difference between breaking load of the rope and braking load of the joint on the rope we conducted additional laboratory testings, the results of which are presented in this paper.

Testings of the breaking load of the rope and joints

The former testings comprised testing of various types and constructions of ropes, which are used to form a diamond wire. In the meantime most of the users in Croatia have accepted the round strand rope as the most useful one (Fig. 3) with constructions (1+6+12)+6(1+6). This rope construction proved as the best one in former testings too. Therefore, these testings comprised determination of breaking load of the rope of this construction and breaking load of the same ropes connected by two kinds of joints. The ropes made by 4 manufacturers were tested and sleeve couplings and joints with "male-female" threads were used for connecting. Connecting was done on a standard device which is used upon shaping of diamond wire (diamond wire bench assembling unit) by the workers of particular users in the way as they do it for their everyday use. Although all the ropes had the same bacis construction they differed among each other to a certain extent in the strength of steel and minor construction details.

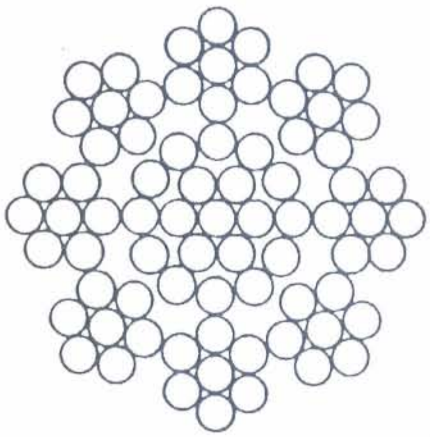

Fig. 3. Cross-section of the tested ropes
Sl. 3. Presjek ispitivanih užeta

In these testings the real breaking load was only determined by breaking of the rope as a whole, in difference to the earlier testings, when this load was determined by testing of specific wire samples and summing up their values. Upon the testing of the rope by its breaking as a whole appears gradual breaking of some wires within specific force and loosening of the strength (Fig. 4). The indicator of the testing instruments registers the load which causes the damages of some wires, not the rope braking. This load is regarded as relevant for determination of the allowed tensile strengths.

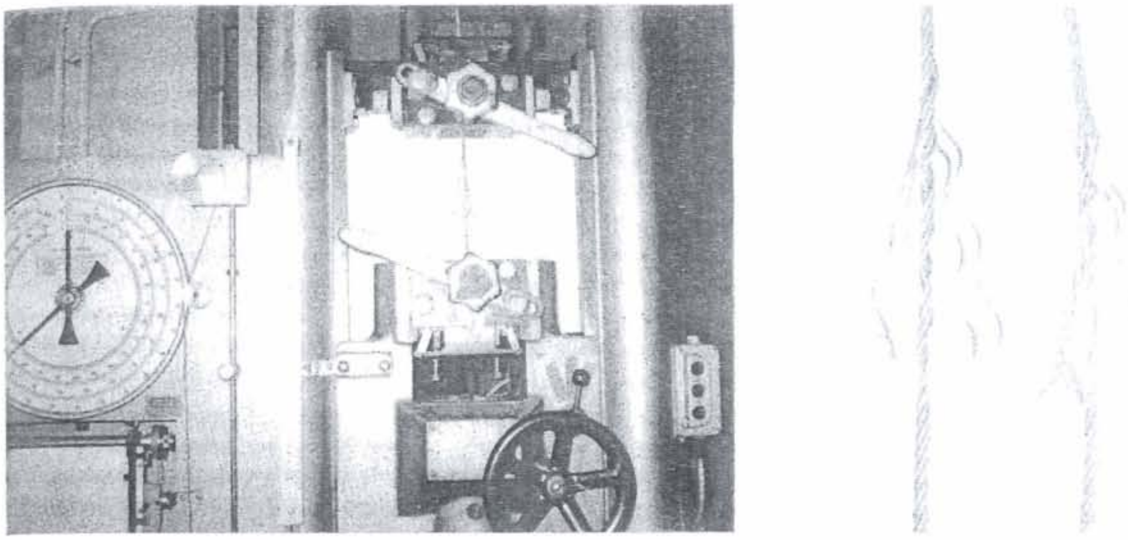

Fig. 4. Way of rope breaking
Sl. 4. Način prekida užeta

During the testings of breaking load of rope joints breaking was in most cases caused by pulling out of the rope from the joint (Fig. 5), whilst only in a small number of cases the ropes broke along the edge of the joint (Fig. 6). Strictly speaking, during the testings of joints with "male-female" thread the rope was pulled out from the joint in

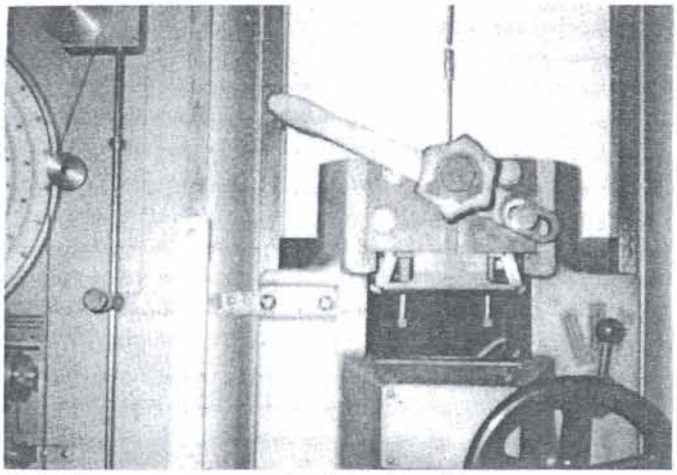

Fig. 5. The most common way of breaking of rope joints
Sl. 5. Najčešći način prekida spojnih mjesta užeta

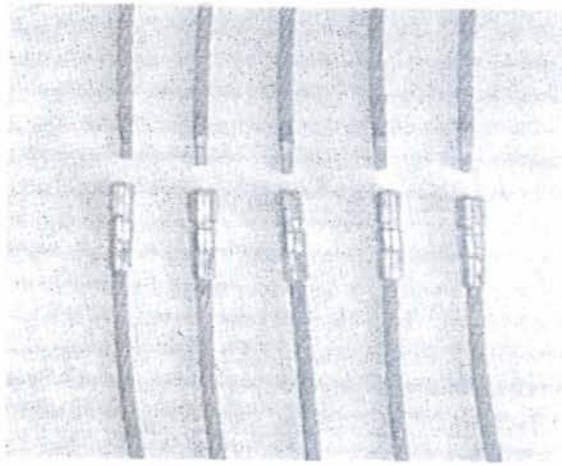

Table 1 Concise results of testings of breaking load of ropes and joints
Tablica 1 Sažeti rezultati ispitivanja prekidnih sila užeta i spojnica

ROPES NO.	**1**	**2**	**3**	**4**
Minimum breaking load, N	17 260	12 259	15 838	15 966
Maximum breaking load, N	18 290	14 367	17 211	16 476
Average breaking load, N	17 898	13 779	16 721	16 051
THREADED JOINTS ON ROPES NO.	**1**	**2**	**3**	**4**
Minimum breaking load, N	4 492	4 904	4 521	4 865
Maximum breaking load, N	6 100	6 865	6 473	6 360
Average breaking load, N	4 805	5 954	5 374	5 260
SLEEVE COUPLINGS ON ROPES NO.	**1**	**2**	**3**	**4**
Minimum breaking load, N	1 746	-	3 170	-
Maximum breaking load, N	3 785	-	3 310	-
Average breaking load, N	3 462	-	3 240	-

86.6% cases and in 13.4% cases the rope broke along the edge of the joint, while the rope was pulled out from all the sleeve couplings.

The concise results of the testings of breaking load of diamond wire ropes and joints on them are presented in the Table 1. The names of specific rope manufacturers are not stated in the Table but they are replaced by the numbers 1,2,3 and 4. 25 rope samples (total of 100) were tested from each manufacturer including the total of 100 joints with "male-female" threads and 50 sleeve couplings. The average figures of breaking load of the rope and joints present the mean value of 23 tested samples, because the lowest and the highest values are not included in this average value.

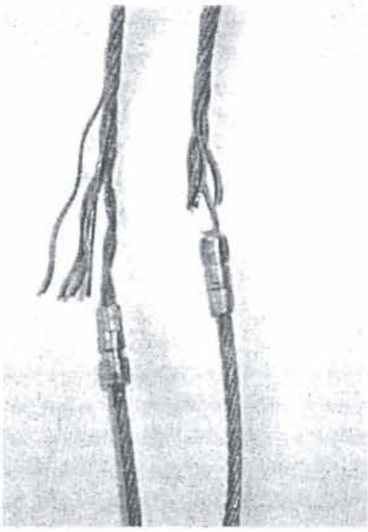

Fig. 6. A more rare way of breaking of rope joints
Sl. 6. Rjeđi način prekida spojnih mjesta užeta

Analysis of the results

The results of the testings (Tab. 1) show that the steel rope of diamond wire, which is used upon sawing of carbonate stone, can resist to approx. 3 times higher tensile strength than the joints connected by "male-female" threads and approx. 5 times higher strength than the joints connected by sleeve couplings. Upon testing of complete rope breaking the average breaking load was 17 898 N for the ropes no. **1**, 13 779 N for the ropes no. **2**, 16 721 N for the ropes no. **3** and 16 051 N for the ropes no. **4.** The highest average value of breaking loads of joints with "male-female" threads was only 5 954 N (ropes no. 2) and 3 462 N (ropes no. 1) for the joints connected by sleeve couplings.

These testings clearly show that the rope can resist to a considerably higher breaking load than the joints can. Accordingly, the critical points of breaking are joints too, not just ropes. This means that it is not necessary to have ropes of high breaking load. More important is for them to be as elastic as possible. Therefore, the softer wire material can additionally increase the rope elasticity.

The diamond wire rope must have a small cross-section and mass but high tensile strength. Such a rope must be elastic and resistant to crushing, torsion, abrasion and corrosion. It is very difficult to select the rope construction which meets all the requirements at the same time, since some of them exclude one another. The wires of larger diameter have higher tensile strength but lower bending strength at the same time and v.v. By increase of wire hardness the tensile strength is increased, but the bending strength is decreased. The tougher material is, the rope is harder and more brittle (the interdependence is not proportional but appears in lower progression). Since the rope joints have considerably smaller breaking resistance than the rope itself, it is useful to use the ropes of lower tensile strength, which at the same time increases its bending strength.

During the testings of joints the breaking on the joint was in most cases caused by the pulling out of the rope from the joint. This brings us to the conclusion that the breaking load of the joint can be increased by better fastening of the joints, i.e. larger pressing upon their fastening. However this is denied by other samples, whereby disconnection was caused by breaking of ropes along the edge of the joint. Tensile strengths, which caused such breaking, were the same or lower than those, which caused pulling out of ropes from the joints. This means that fastened joints with larger pressing cause squeezing and loosing of ropes at the joint, which again means that fastening of joints with larger pressing will not enlarge resistance to breaking of the joint.

The testing results show that the ropes, which are used for shaping of diamond wires, can resist to high breaking load (they have a high pulling strength) i.e such high resistance to breaking is not necessary since the joints between separate rope sections cannot resist to this breaking load anyway. This conclusion is proved by additional testings that we conducted on used ropes. These ropes resisted to approximately the same (in some cases even higher) breaking loads as the new ropes, although the control of the samples showed that in each sample there was a considerable number (8-17%) of broken wires.

The changing tensile strength, bending, rubbing and crushing finally cause breaking of some rope wires. Despite the fact that the broken wire presents the corresponding decrease of the metal cross-section (and safety) of the rope on the breaking point, due to the rubbing it takes over its part of the force in the rope on the particular length. Therefore the broken wire has along its length the limited impact on the tensile resistance of the rope as a whole.

Conclusion

Upon operation diamond wire as a whole and diamond wire rope were stressed by tension, exposed to static and dynamic friction forces as well as to constant bending over small radius of curvature. The rope was also exposed to corrosion and deterioration. The stresses by kinetic impacts were unpleasant. High velocities of diamond wires produce also vibrations of the rope, caused by dynamic forces, which lead to fatigue and recrystallisation of steel. Material fatigue is increased due to the uninterrupted sawing process, because wire material cannot have complete elastic deformations.

Laboratory testings of breaking loads of ropes of diamond wire saws and joints on ropes showed that the rope can resist to a manifold higher breaking load than the joints can. Former trial testings of the ropes (Dunda, 1998) have showed that the increased deterioration of diamond wire is mostly caused by partially too heavy stressing, since the rope is not with its entire surface in contact with the driving pulley, leading pulleys and cutting surface. The beads on the rope are in contact with the coating of the driving pulley, so only some parts of the wire in the rope resist upon the inner ring of the bead. Therefore appears the partial stress and wire crushing which causes the deformation of the rope and its too early deterioration. This is the reason why the rope should be softer and more rounded with decreased internal friction, which appears upon bending in the cut and passing along the pulleys and driving pulley. If the rope had stiffly braided hampen core of appropriate dimensions, it would increase its softness and reduce the friction and stress of the wires upon one another. However, it was thought that the application of the ropes with hampen core on diamond wire saw was not purposeful since such a rope has a decreased metal cross-section. Small diameter of diamond wire rope has already a small metal crosssection, so its additional decrease would substantially reduce the breaking load of the rope. The ratio of the metal cross-section and the cross-section of the circumscribed circle around the cross-section of the normal strand ropes with hampen core is approx. 0.47 and approx. 0.75 with spiral strand ropes. The presented laboratory testings of breaking load of ropes and joints show that even a rope with such reduced cross-section would have sufficient i.e. higher breaking load than the joint. This means that standard stranded ropes for general purpose (DIN 3055, DIN 3060) consisting of 6 rounded strands arranged concentrically around hampen core could be used as ropes of diamond wire saws (Fig. 7). Hampen core serves as elastic "placenta" and a reservoir of grease for strands and wires, which also influences the extension of durability of ropes.

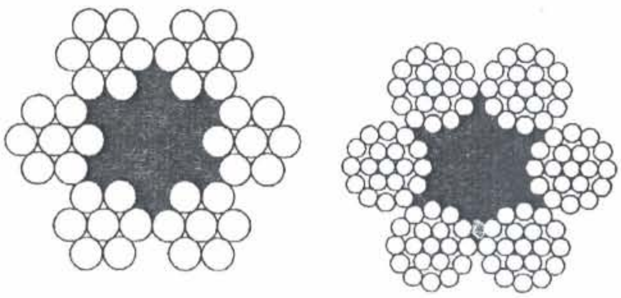

Fig. 7. Suggested standard stranded ropes with hampen core [(j+6(1+6)] and [j+6(1+6+12)]
Sl. 7. Predložena obična pramena užad s konopljinom srčikom [j+6(1+6) i [j+6(1+6+12)]

Since diamond wire rope is small in diameter (5mm) it is certain that spiral ropes will further be used in a considerable number of cases. The results of the presented testings show that the wires of such ropes should be made of softer steel. In our opinion the ropes should be constructed with fillers. The ropes with round strands have emptiness in the strands which decreases the homogenity of the rope. In order to reduce the squeezing of the wires in the rope, which is the consequence of these empty spaces, thin filler wires are put among the wires (with some constructions), but they are not load bearling wires. This enables better contact of the wires in strands and better elasticity of the rope. The diamond wire rope has smaller empty spaces in the strands because of the small wire cross-sections (smaller than the usual ones in the filler wires), so the wire filling of the strands would not have any purpose. However, the empty spaces among strands in these spiral strand ropes cause the increased friction and stress of the wires upon one another. Therefore we think that the construction of the rope, which would have hempen (or even better synthetic) fibre filling would show longer durability than the existing ropes. Such possible rope construction (Fig. 8) would not be different than the existing ones, except the fact that it would have synthetic fibres of a small cross-section as a filler. These fillers would increase the homogenity of the rope, the strands would not have punctual contact, but the contact surface would be spread on the synthetic inserts, which would decrease crushing caused by the elements of the diamond wire (especially beads). This is especially visible upon bending along a small radius of curvature. Synthetic fibres would take over the role of the hempen core to some extent by making the rope softer, but they would not reduce its load bearing capacity, because the metal cross-section would remain the same. The increased softness of the rope would reduce the internal friction upon bending along the pulleys and in the cut, which would decrease deterioration and prolong the durability of the rope.

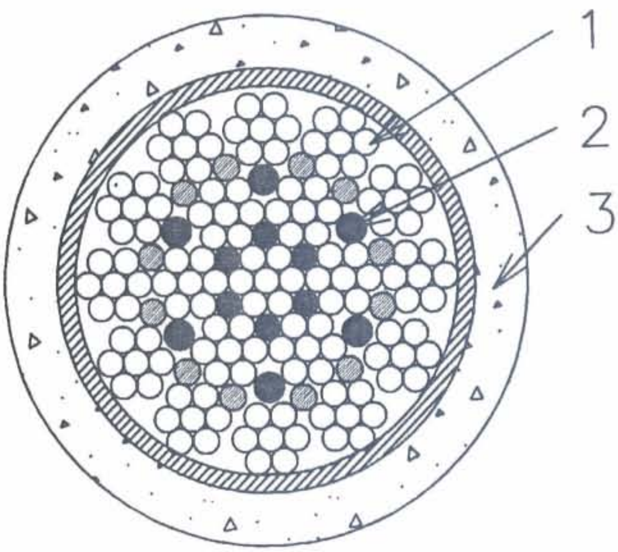

Fig. 8. Proposal of a new construction of ropes for diamond wire, 1) steel wire, 2) synthetic fibre, 3) diamond beads
Sl. 8. Prijedlog nove konstrukcije užeta za dijamantnu žicu, 1) čelična žica, 2) sintetička nit, 3) dijamantne perle

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