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CHANGES IN PROPERTIES AND THE INTERNAL STRUCTURE OF POLYETHYLENE POLYMER RAILWAY SLEEPERS

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Abstract

Elements of the railway infrastructure are subject to difficult weather conditions, as well as changing dynamic loads resulting from the operation of a given part of the infrastructure. The following article presents an analysis of the internal macro and microstructure of a polymer railway sleeper made of reinforced polyethylene. The aim of the research was to obtain the results of structure, analysis of hardness measurements and identification of structure inconsistencies and the presence of other structural components in recycled polyethylene substrates. In terms of the tested material properties of the polyethylene sleepers, no significant changes in strength and plastic stability were found for the samples made of polyethylene tested before and after exposure to varying atmospheric conditions in the climatic chamber.

Keywords: polyethylene, railway sleepers, structure, mechanical properties

1. INTRODUCTION

Maintaining the railway infrastructure in a condition that ensures safe railway traffic is the basic duty of the railway infrastructure managers under the Act on Railway Transport. Elements of the railway infrastructure are exposed to difficult weather conditions, as well as changing dynamic loads resulting from the operation of a given part of the infrastructure. The lack of proper track maintenance has a negative impact on their operation, causing: lowering the permissible speed, reducing the smoothness of driving, lowering the safety of rail traffic, increasing the degradation of aggregate and railway subgrade/ballast, and increasing the impact of dynamic impacts on the surrounding buildings. Investigating and analysing the most common changes in properties and structure, it will be possible to identify the root causes that make it necessary to replace and/or detect them, and propose countermeasures to extend the product life cycle.

1.1. Railway sleepers from plastic

Polymeric materials, also commonly referred to as ‘plastics’, constitute a very broad group of materials firmly established in the construction industry. They are also used in railways. Attempts were made to use both curable and thermoplastic plastics for railway sleepers.

Thermoset plastics are used in the case of polymer-mineral composites, commonly referred to as polymer concrete. Usually, the matrix is a polyester resin and the fillers are gravel, ash, sand, etc. Less common is the use of epoxy or vinyl ester resins. The lower cost of polyester or vinyl ester resins compared to epoxy resins promotes the use of the former. However, the mechanical and thermal properties, high moisture resistance, low shrinkage, and high elongation, argue in favour of epoxy [1-5].

The most popular group of polymer materials is thermoplastics, which have been used in railway sleepers for nearly a decade and a half. The peculiarities of the railway market, which require long-term testing of a new product, mean that these sleepers are still not very commonly used. Some polymer sleepers are still being tested on test tracks. The approval tests are lengthy because of the need to ensure a high level of safety for travellers. Thermoplastic sleepers can be seen not only on test tracks but also, increasingly, on regular lines, on almost every continent [6,7]. In Poland, polymer sleepers do not have technical approval for railway use.

The main advantages of using thermoplastic primers are economic, technological, and improved performance. The manufacturers [8,9] of polymeric primers highlight many of these and they include the following:

- the possibility of using the same equipment as for wooden sleepers,
- standardised systems for fastening rails to the sleeper can be used,

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- The sleepers can be made of recycled polymeric materials and recycling is possible after a period of use,
- they do not rot, crack, or become impermeable to moisture,
- are resistant to the effects of gouging insects such as woodworms, ants, etc.
- have a very high chemical resistance.

Unfortunately, one has to be sceptical about the advantages presented. Polymeric materials are also subject to ageing and degradation, especially under the combined effects of chemical agents, such as UV radiation, high temperature, ozone, and mechanical stress [10, 11].

Furthermore, the reuse of polymeric materials in railway sleepers is questionable as the material can be of poor quality after a long period of use due to the ageing processes it will be subjected to. After such a long service life as is anticipated, the polymer sleeper may no longer be a suitable raw material for further processing [6, 12].

Another problem is the rheological properties of polymeric materials. These materials are much less resistant to creep and stress relaxation processes compared to other groups of materials.

Manufacturers combat these disadvantages by adding various additives to the material (flame retardants, fillers, anti-ageing substances, etc.). The additives introduced make it a formally a composite material.

Compared with traditional wooden sleepers and cement sleepers, it has the characteristics of simple construction and installation, longer service life, more waterproof, fireproof and insect-proof, and recyclable, as well as the features of lighter weight, higher strength and corrosion resistance, better insulation performance, easier processing, no water absorption, etc.

1.2. Polyethylene railway sleepers

The most obvious and predictable material is high-density polyethylene (HDPE). This is one of the cheapest and most accessible polymeric material whose properties are likely to meet the demands of railway sleepers.

In 2021, the market volume of the thermoplastic polyethylene amounted to nearly 107 million metric tons worldwide. As estimated by 2029, the global market volume of polyethylene is expected to rise to around 130 million metric tons [13].

In 2021, the distribution of the global polyethylene production was about 14,4 % of all kinds of plastics. This was the second place behind polypropylene (19,3 %). In the same year, European plastic production reached 57.2 Mt. Post-consumer recycled plastics and bio-based/bio-attributed plastics, respectively accounted for 10,1% and 2,3% of the European plastics production. For the production of railway sleepers this is a great opportunity to source cheap, sustainable, and environmentally friendly material [14].

Fig. 1. Polyethylene railway sleepers

Other alternatives are blends of recycled materials: a mixture of polyolefins (PP, HDPE), polyethylene terephthalate (PET), and high-density polyethylene (HDPE). However, the blends of different plastics used present technical difficulties. A compatibiliser must be used to enable processing because of the different transformation temperatures. Compatibilizers are additives that allow two polymers to bond together and stabilise each other, resulting in an enhanced end product. These additives make it easier to recycle plastics, as many of the plastic blends collected for recycling do not mix or adhere well [15-17].

The following investigations are a presentation of the completed research work, bringing the goal of the work closer to completion and proving the purposefulness and put forward in it. This research consists of testing samples of polymer underlays obtained from two different stages of the used materials: polyethylene after and before the long-term cyclic treatment in an climatic chamber. In addition, the impact of innovative railway sleepers on the financial aspect of the company was also underlined, because of the practical implications of such work.

2. MATERIALS FOR INVESTIGATIONS

The polymer substrate used for the tests is made of high-quality, ductile plastic with steel reinforcing bars covered, which ensures both high strength properties and excellent damping properties.

For the investigation, the polyethylene sleeper was used in its cross-sections presented in Figs. 2 and 3), taken from the inside as well as outside of one sleeper.

The polymeric materials used in railway sleepers differ not only in their chemical structure but also in their type of structure.

The most common types of polymer sleeper structure are: homogeneous structure sleepers, multilayer structure sleepers, foamed sleepers, and "reinforced" sleepers. Some types of this structures are visible on figure 2 (#1 foamed structure, #2 reinforced structure, #3 homogeneous structure).

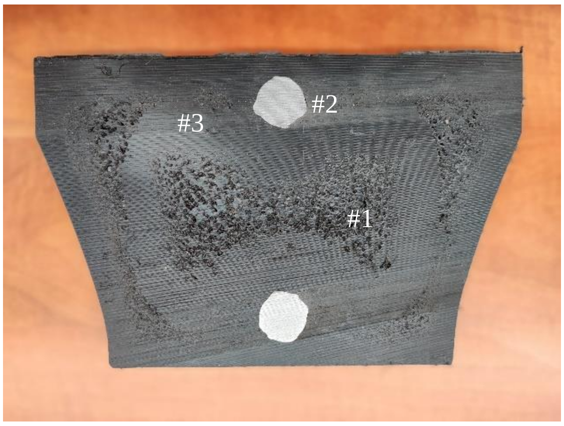

Fig. 2. Cross-section of the investigated sleeper – outer part of the sleeper

Fig. 3. Cross-section of the investigated sleeper – middle part of the sleeper

Substrates with a homogeneous structure are possible to produce; however, it is not easy to comply with the technological parameters that will ensure such a structure. The most important parameters that significantly affect the structure of polymeric products are the pressure, temperature, and duration of the various processing phases. Polymer plastic processing avoids the manufacture of bulk products with large volumes, such as shrinkage cavities, air voids, and similar defects developed in the products. In addition, they require controlled long cooling in the mould, which prolongs the entire production cycle. Cooling without a proper regime will result in pores, cracks, and other defects in the structure (Fig. 4).

Sleepers with multilayer structures are rarely achieved by deliberate action. Rather, it is the result of manufacturing technology specifications (e.g. extrusion) and technological errors encountered during the manufacture of thick-walled products. Typical large-format technologies, invented precisely to avoid structural defects, are not applicable in this case. Rotoforming, thermoforming, gas injection, or extrusion blow moulding techniques will produce only a hollow shell. These technologies can create the appearance of producing an apparently solid but hollow component.

Fig. 4. Example of poor structure of an HDPE product cast without regime pressure

Another type of structure for polymer sleepers is the foamed structure. This type of sleeper is relatively lightweight and can be shortened and cut with conventional woodworking tools. Railway sleepers made of foamed polyurethane reinforced with long glass fibres were used in the renovation of the Zollant Bridge (Austria) [16, 6].

The last type of sleeper is the one in which reinforcement bars are used that reinforce the sleeper in a similar way to those used in concrete sleepers. In this case, steel, glass, or basalt rods are used as reinforcement bars. In this case, the most important aspect is to ensure high adhesion between the components of the product. In our case, a unique steel reinforcement was used in this recycled plastic sleeper. To achieve the required stiffness and strength, the polymer sleepers were found to be reinforced with 2 or 4 steel rods using a unique manufacturing process developed and patented by the manufacturing company. The steel reinforcing bars are fully integrated and embedded in the plastic pad during the moulding process.

The technological process of manufacturing the tested primers created a complicated structure. In addition to the reinforcing bars, the solid layer and foam layers can be seen in the cross-sectional images (Figs. 2 and 3). The foam structure is the result of the appearance of pores during the cooling of the plastic. This is caused by inappropriate temperature and pressure during this phase of the process. The foam areas are an error resulting from the adopted manufacturing technology rather than a targeted procedure.

3. INVESTIGATIONS PROCEDURE

Samples were cut from the railway sleeper. The first group of samples constituted as the reference material. The second group was aged in a climate chamber. Both groups were tested for changes in hardness and compressive strength. Before all tests, the test samples were conditioned for 24 hours at the temperature (22±1)°C and relative humidity (50±5)%.

3.1. Ageing procedure

Climate chamber exposure is a process in which materials and products are subjected to controlled temperature and humidity conditions to assess their strength and durability under different environmental conditions. The test is carried out using a device that allows the simulation of various environmental conditions such as extreme temperatures, humidity, UV radiation, pressure changes, etc. This makes it possible to test products and materials for the effects of the applied exposure conditions (controlled temperature and humidity conditions) in the climate chamber on the materials tested. During exposure in the climate chamber, the material or product is placed in a chamber simulating the environmental conditions. This process can last from a few hours to several weeks, depending on the required length of the test. Due to the fact that there are variable atmospheric conditions on the railway lines due to both changes in temperature during the year and changes in humidity, it was decided by the company that it was necessary to investigate the effects of variable atmospheric conditions on both types of polymer railway sleepers. The tests were carried out in the ATT Discovery CS640 climate chamber. Exposure in the climate chamber was conducted using the following conditions and measurement parameters (Table 1).

Table 1. Parameters of climatic chamber exposure (T – transition, E – exposure)

Number of cycles performed:				**50**
One cycle procedure:				
Param.	T 1	E 1	T 2	E 2
Temp.	+80°C	+80°C	-40°C	-40°C
Humid.	90%	90%	90%	90%
Time	1h	3h	1h	3h

3.2. Hardness testing

In the Shore hardness test, the indentation depth is measured using a spring-loaded indenter made of hardened steel to indent the material/species. The indentation depth is a measurement of Shore hardness, which is determined on a scale of 0 Shore (2.5 millimetre indentation depth) to 100 Shore (0 millimetre indentation depth). A range of different shore scales have been established based on a variation in indenter form and spring characteristics. The most well-known scales are Shore A and Shore D. Shore D hardness is a standardised test that consists of measuring the depth of penetration of a specific indenter. The hardness value is determined by the penetration of the durometer indenter foot into the sample. The Harder elastomers, plastics, and rigid thermoplastics according to Shore are determined using the test procedure standardised to PN-EN ISO 868:2005.

Investigations were caried out in accordance with parameters listed below:

- Measuring range: 0-100 Sh D,
- Resolution: 1 Sh D,
- Maximum error: +/-3 Sh D,
- Measuring force: 0-44.5 N,
- Indentor: Tapered, truncated, steel,
- Pressure foot diameter: 16 mm.

We distinguished several zones in the tested sleepers. The observed zones are the result of different cooling intensities of the thermoplastic material during solidification (Fig 5).

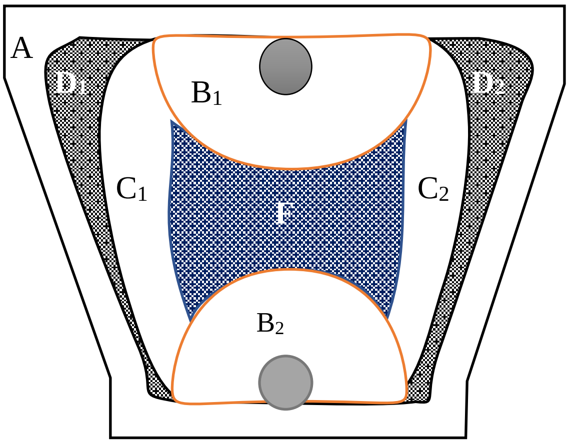

Fig. 5. Zones highlighted in the polymer sleepers under test (description of the figure in the text)

The ‘A’ zone is a strip of material approximately 10-18 mm wide, bordered by the edge of the test specimen. In this zone, 24 hardness measurements were taken, 6 on each side (right, left, top, bottom). The next zone (‘B_1’ and ‘B2’) is the surface of two half circles with steel reinforcement bars in their centre. The circular shape of these zones is due to the intensive cooling of the material through the steel bars, which in this case act as heat sinks. In these zones, 12 hardness measurements were taken, 6 in each zone ('B1', 'B2').

Zones 'D1', 'D2', and ‘F’ are highly porous areas in which shrinkage voids have formed. In these zones, voids vary in size and, in some places, occur in more homogeneous areas. Hardness measurements were taken in these areas. Six hardness measurements were taken in each zone.

The zones 'C1' and ‘C2’ have a homogeneous structure. Its appearance between the porous zones can only be explained by the synergistic effect of the cooling of the mould in which the sleeper was formed and the intense cooling coming from the reinforcement bars. Six hardness measurements were taken in each zone, too.

Shore D hardness results and standard deviation values are shown in Tables 2 and 3.

Table 2. Results of Shore D hardness measurements, reference samples

Zone	Hardness [HD]	Standard deviation
A	61,2	0,88
B_1	58,9	2,54
B_2	58,9	1,66
C_1	61,2	1,03
C_2	61,4	0,86
D_1	36,0	3,51
D_2	36,8	7,08
F	44,8	6,87

Table 3. Results of Shore D hardness measurements, samples after ageing in in the environment chamber

Zone	Hardness [HD]	Standard deviation
A	57,4	4,11
B_1	58,2	3,23
B_2	58,6	2,87
C_1	56,8	4,20
C_2	55,6	4,40
D_1	35,2	9,65
D_2	30,6	10,53
F	32,0	12,18

Comparing the hardness values obtained, it can be seen that the least change occurs in areas B1 and B2. In these areas, the decrease in hardness is approximately 1 %. The greatest change was observed in area F, the central area with the highest number of pores. Here, a 29 % decrease in the hardness on the Shore D scale was measured. It is worth noting the increase in the standard deviation values compared to the reference samples. The increase in the spread of measured values is typical of degradation processes in polymeric materials.

The observed changes in the hardness of the polymer material are due to remodeling of the internal structure caused by shortening of the polymer chains due to thermal degradation and chemical reaction of the newly formed chain ends. This process is widely reported in the literature [18, 19]. In addition, changes in mechanical properties due to the presence of pores in the polymer structure are to be expected. Long-term thermal exposure promotes rheological processes such as creep and stress relaxation, which will affect homogeneous and porous structures to varying degrees.

3.3. Compressive strength test

The compressive strength test is one of the basic mechanical tests used to assess the properties of materials. This test allows to determine the force needed to destroy a sample subjected to uniform compression in the direction of an axis perpendicular to its surface.

The main reason for choosing a compression test to evaluate the strength properties of polymer railway sleepers was that the evaluation could be carried out in different sleeper areas. Other static strength tests, due to the shape of the specimens, did not allow the test to be performed.

However, unlike conventional construction materials which have well-documented behavior in service, there is virtually no reliable data on the in-test behavior of HDPE in compression [21]. Second problem is that most HDPE used in sleepers is recycled material. The physical and engineering properties of recycled HDPE typically exhibit a high coefficient of variation [22, 23].

The compression curve obtained in the test is difficult to interpret, as brittle fracture of the specimens is rare in plastics. Additionally, the curve can have various shapes (Fig. 6).

The course of the compressive strength curve depends on many factors, including the type and structure of the polymer, the degree of crystallinity, the conditions of the production process, as well as the chemical properties of the material. Atmospheric factors such as temperature, humidity, pressure, and load speed can also affect the curve.

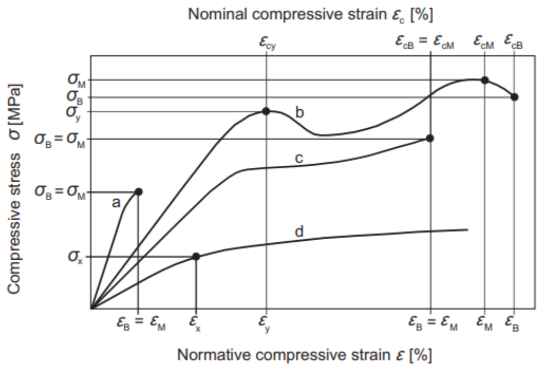

Fig. 6. Typical compressive stress (σ)–compressive strain (ε) diagrams of polymers in the compression test; brittle plastic (a), ductile material with compressive yield stress (b), ductile material without compressive yield stress (c) and ductile plastics without break (d) [18, 19]

The compressive strength test was carried out in accordance with the European standard PN-EN ISO 604:2006 Plastics. Determination of compression properties using the following parameters and test conditions:

- sample dimensions: 25x25x25 mm (Fig 7);
- number of test samples: 5;
- testing speed: 1mm/min.

The test was carried out using the LabTest 6.100 universal testing machine from LaborTech, accuracy class I, and the compression of the samples was carried out between two steel plates.

Due to the dependence on software and test equipment and the possibility of failure, compressive stresses at break should not be used [24].

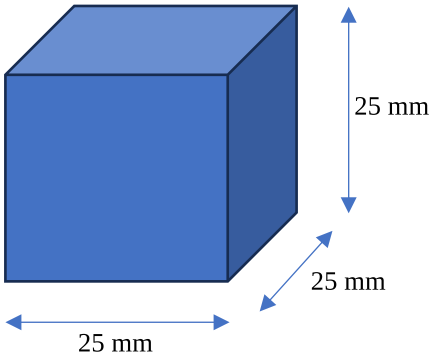

Fig. 7. Shape and dimensions of the used specimens for the compressive strength test

For these reasons, it was decided to run the tests until a stress of 20 MPa was reached. The shape of the obtained curves in this range was analysed.

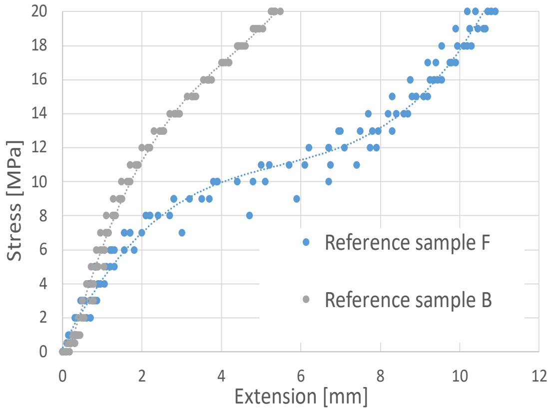

Fig. 8. Comparison of the shape of the compression curves of the specimens: B - taken from area B (homogeneous structure), F - taken from area F (porous material structure)

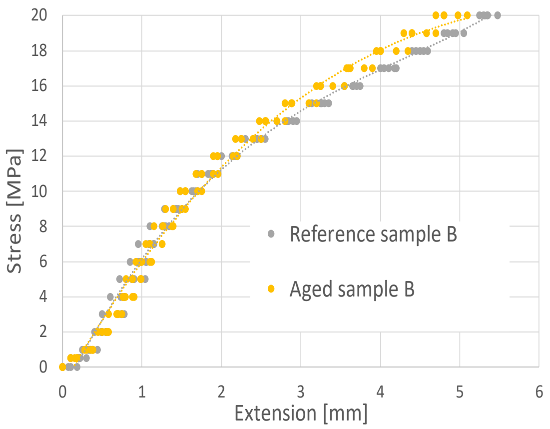

Fig. 9. Compressive strength test curves of the homogenous material before and after the simulation in the environment chamber

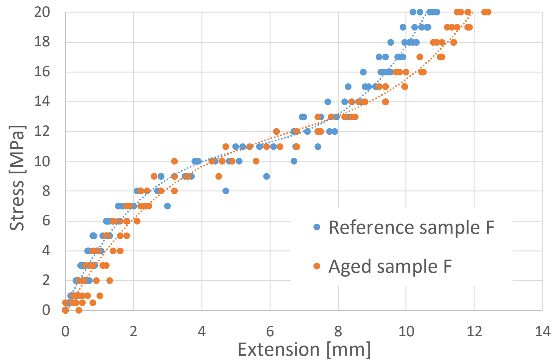

Fig. 10. Compressive strength test curves of the porous material before and after the simulation in the environment chamber

Compressive strength diagrams of polymeric materials show their ability to hold a load during compression along an axis perpendicular to the direction of force application. The graphs shown in Figures 8 to 10 have a characteristic curve that describes the behavior of the material during the compression process.

The greatest differences in the curves can be seen in figure 8, which shows the compression plots of porous samples taken from the core of the deposit compared to samples with a homogeneous structure. The sample with a large number of pores undergoes greater deformation to undergo almost the same compressive strength as the homogeneous material after compaction.

After exposure in the climatic chamber, the samples of HDPE sleepers obtain compressive strength similar to that of unexposed samples, however, they achieve similar values at lower deformation of the tested sample (Figs. 9 and 10). The reference samples have a slightly greater stiffness.

Figure 11 shows samples after the compressive strength test, taken from porous area of a railway sleeper made of polyethylene. On the left side of the picture we see the sample before exposure in the climatic chamber (a) and on the right side of the picture we see the sample after exposure in the climatic chamber (b).

a) b)

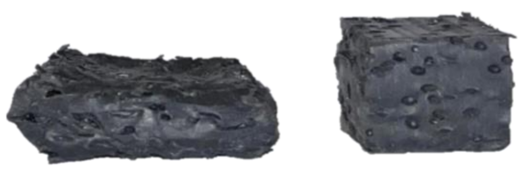

Fig. 11. Investigeted samples in the compression test: a) – references sample, b) – aged samples

4. CONCLUSIONS

The innovatory railway sleepers were successful to undergo a simulation of the influence of temperature on the properties and characteristics of the undercoat. In general, such a solution of using recycled polymer materials for new railway sleepers can be very attractive from different points of view, e.g., it can:

- confirm of the possibility of recycling,
- help in reducing the costs of railway infrastructure repairs,
- reduced environmental impact.

Particularly it was found that:

1. It was found that the carried-out tests and analysis of the impact of cyclic changes in environmental conditions has led to only small changes in the hardness and strengthening properties of polymeric materials used for railway sleepers, reaching only 1|%.
2. In terms of microstructure, the inner stability of the sleeper was changed in such a way that the strengthening rod has lost its integrity with the polyethylene matrix, after holding in the environmental chamber. Values of these changes were not measured, but only evaluated using optical micrographs revealing optical contrast.
3. There are observed large differences in hardness, reaching even more than 29% between the particular areas of the sleepers cross-section. The main factor influencing the hardness is the porosity and the microstructure and that fore the density of the sleeper materials which strongly depends on the manufacturing procedure and quality of the products.
4. The compressive strength test curves of the porous material before and after the simulation in the environment chamber reveals increase of the measured stress values. For the samples before environmental influence, the compressive strength achieves higher values compared to the material after exposure in the environmental chamber, reaching event 25%.
5. In terms of the tested material properties of the polyethylene sleepers, no significant changes in strength and plastic stability were found for samples made of polyethylene tested before and after exposure to changing weather conditions in the climatic chamber. This is a significant finding, because of the possibility of application in real conditions.

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