

Article

Effectiveness of Sorbents in the Equipment of Firefighting Units in Practice

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Abstract: The presented study deals with the effectiveness of sorbents in the equipment of firefighting units in Slovakia. Currently, there are many manufacturers of sorbents on the market and also a number of types of these products. As a result of an emergency on the road, especially in the case of traffic accidents, there can be a leakage of dangerous substances. From this point of view, it is necessary to prevent the dangerous substance escaping into the environment as quickly as possible and to choose a suitable sorption material to prevent the leakage. For the stated reasons, the aim of the submitted paper was to research the effectiveness of sorbents used by fire brigades in the Slovak Republic in traffic accidents. Part of the publication is on the specification of sorbents, and as part of the research there is an evaluation of their composition and a description, and according to the method and the successive laboratory tests, the operating fluid that is applied to the selected sorbents. After the test and the resulting values, the initial and absorbed weight of the sorbents were determined. The sorption capacity and absorbency were determined from the resulting values. The time factor and the ability to remove adsorbed sorbents from solid surfaces was evaluated after visualizing the process and the final result. The resulting values were unified and compared with other sorbents, where their suitability for the purposes of firefighting units in practice was determined.

Keywords: traffic accident; sorbent; fire department; dangerous substance



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1. Introduction

Under normal conditions, traffic accidents are a frequent cause of emergency events, where dangerous substances can leak. A specific type of such an emergency is the release of dangerous substances into the environment, where such a release can cause serious consequences, as it can contaminate groundwater, springs, soil and even the human body [1].

When a dangerous substance is released, the threat is the substance itself or its concentration with another substance or with air. For this reason, Safety Data Sheets are presented in the industrial environment, which serve to identify the substance and its physical and chemical properties [2,3].

In the case of road and rail transport, the Kemler code and the UN code are used, which can quickly identify the transported substance and its possible dangers by their display. Thanks to these identifications, it is possible to prevent leakage as best as possible, use the most suitable means, and deal with the subsequent disposal [4,5].

Among the most frequent emergency events with the release of dangerous substances the following can be included:

- Accident with the release of chemical substances
- Accident with the release of radioactive substances
- Accident with leakage of petroleum substances and products [6].

The fire and rescue service plays an important role in the prevention and subsequent disposal of hazardous substances in accidents concerning the release of a hazardous substance, according to its technical properties, material equipment used, and safety. An important part is the correct selection of the procedure and distribution of available forces so that there is no subsequent accumulation and uncontrollable leakage [7].

The fire and rescue service mainly performs the following tasks in the event of a hazardous substance leak:

1. Minimization of risks and stabilization of leakage.
2. On the basis of determined internal procedures, disposes of the leakage of a dangerous substance.
3. Based on the number of responding firefighters, they conduct a survey and subsequent decontamination of the area [8].

The procedure itself after arriving at the intervention site can be defined as follows:

- Note the direction of the wind and constantly check it.
- The vicinity of the accident is not approached with mobile technology.

The main task is to take the following measures:

1. Take measures to save people, animals and the environment
2. Research, to find out what substance it is and identify it.
3. Summon reinforcement units that are trained to work with hazardous substances, or cooperate with the control chemical laboratory of civil protection.
4. Carry out activities to minimize and eliminate the scope of the accident.

In the event that the fire brigade cannot identify a dangerous substance, the following procedure is followed:

1. Closure of the place (zone of direct danger, border of the security zone).
2. Allocation of initiation resources.
3. Deployment of a small number of firefighters who, in the zone of direct danger, will carry out research and work in the given zone.
4. Preparation of the workplace for decontamination.
5. If the situation allows, take measures to capture and remove the dangerous substance.
6. Evaluation of the current situation [9–12].

The fire and rescue service most often has the following technical and material equipment to prevent the leakage of dangerous substances:

- sorbents,
- detection by technical means
- means for collecting dangerous substances
- means for capturing dangerous substances
- sealing means for sealing the leakage of a dangerous substance
- pumping units and pumps
- constituent substances [13,14].

Sorbents

Sorbents can be defined as natural or artificially created chemical substances that are mostly in a solid state. They can absorb or adsorb dangerous substances [15].

When a liquid leaks from a different source of leakage into the external environment, the leaked liquid is captured using sorbent materials and substances that are capable of binding to the leaking substance. For these purposes, it is necessary to define whether the sorbent is an adsorbent or an absorbent. The adsorbent absorbs the liquid on the surface and the absorbent absorbs it into its internal volume. The processes are called adsorption and absorption [16].

Sorbents are substances of first intervention in traffic accidents and industrial accidents. They capture organic and inorganic substances (acids, bases, oil substances and water pollutants).

Their requirements are as follows:

- absorbency
- stability—resistance to acids, solvents
- non-toxicity—they play an important role when used on waterways; they need to get rid of oil substances from the water surface, but they cannot enrich the water with toxicity
- sorption capacity,
- disposal—takes place with the help of washing, where the sorbent gets rid of the contained substances. Carried out by burning in special incinerators. Neutralization is needed [17,18].

Sorbents are most often used on solid surfaces or water surfaces. On a solid surface, they dry on where there is a leaked liquid spilled on a reinforced surface with a small layer. They are used on waterways for capture and subsequent collection. They are stored in loose or textile form on the water surface, where they are bounded by a burrow wall or a sorption snake to prevent scattering on the water surface [19–21].

The division of sorbents is possible based on various criteria, the most common of which is according to their chemical composition, chemical and physical properties, and origin [22].

1. Division according to chemical and physical composition:

- (a) Chemical and universal—their properties are almost identical. Chemical sorbents have a higher resistance to the effects of aggressive substances. They remove oil substances as well as solutions made from water, acids, and alcohols. Some chemical sorbents can be neutralized during sorption. Mostly, their colour version is pink, yellow, or white. They are used in all branches and industries where dangerous substances are found. They are also called cleaning sorbents.
- (b) Oil—designed exclusively for the sorption of petroleum substances. The property that oil sorbents have is ensured by the hydrophobic treatment of the sorbent. Hydrophilicity decreases and hydrophobicity increases to oil substances. This treatment ensures that the sorbent stays on the surface and can be removed more easily. They are used in waterways where selectivity is required in the removal of oil substances. They can also be removed from solid surfaces [23,24].

2. Division according to consistency (shape):

- (a) Loose—sorbent is granulated or powdered and substances in a solid state where they have different chemical or natural compositions. The ability to absorb a large amount of liquid is their great advantage. In this way, they are able to make the place of the leak accessible and a return back to normal in the shortest possible time. They are used on large surfaces and with a small volume of leaking liquid. Storage options are an advantage. The disadvantage is dustiness. Removal from solid surfaces can be difficult.
- (b) Textile—the opposite of loose sorbents. They are useful when there is a small area and a large amount of leaking liquid with the ability to remove various types of liquids. They are composed of polypropylene and microfiber fleece that can absorb liquids. Their sorption value is important—20 L of liquid per 1 kg of sorbent. They have different shapes (mat, pillow, snake...) and colours—white (petroleum), gray (universal), yellow and pink (chemical). The advantage is easy handling, long storage time, and low weight [25–28].

3. Distribution by origin:

- (a) Natural—peat, bentonite, sawdust. They are used in the rough removal of oil substances from soil and water. They cannot remove to a large extent the

amount of leaking liquid. They are rather preventive in nature. The advantage is low price and availability. Their use is for common situations.

- (b) Synthetic—created to remove hydrocarbon pollution. The surface of the sorbent is arranged in such a way that it can absorb the leaking liquid into the pores located on it. Synthetic sorbents have events that are assessed. These are pore soaks and inter-pore soaks.
 - (c) Carbonaceous—use in environmental protection. They are carbonaceous natural sorbents based on carbonaceous materials (coke, activated carbon, carbonaceous molecular networks) [29,30].
4. Division according to reaction from water:
- (a) A hydrophobic sorbent is understood to be a material that is difficult or not at all absorbed by water. Its surface is resistant to becoming wet, and water forms on it in the form of small drops that usually run off. Hydrophobic sorbents tend to remove contaminants that have the same hydrophobic nature, such as oil, grease, or other types of grease. Due to their resistance to water, hydrophobic sorbents are used in applications where it is necessary to separate water and oil substances, for example in the cleaning of oil stains on water or in the separation of water and oil in an industrial environment.
 - (b) Hydrophilic sorbents have the ability to absorb and retain water and aqueous solutions. Their surface is able to attract water molecules and effectively bind them. These sorbents are often used to capture and retain water pollutants such as various chemicals, dyes, and organic compounds. Hydrophilic sorbents are often used in various applications, such as in wastewater treatment, industrial filtration, and production of hygiene products [31].

2. Materials and Methods

The main goal was to verify the properties of sorbents, which are used by the Fire and Rescue Service in emergency incidents involving the release of dangerous substances. The research showed whether the given sorbents met the necessary conditions for the inclusion of sorbents in the use of firefighting units. The evaluation of sorbents took place in the testing of sorption capacity, absorbency, time factor, and removal from a solid surface on operating fluids found in road transport and transport. The effectiveness of the sorbents was verified using visual evaluations and the ASTM F726-06 method. This most up-to-date method defines the evaluation of sorbents based on sorption capacity and absorbency [32–36].

2.1. Loose Sorption Materials in the Equipment of the Fire and Rescue Service

The Fire and Rescue Service uses types of sorbents to remove the consequences of emergency events. They are mostly loose and textile sorbents. Among the best-known sorbents is Vapex or expanded Perlite. In today's world, there are many different sorbent materials on the market that can offer a high preventive protection when disposing of leaking liquids [37].

Their use is primarily preventive protection against environmental pollution and threats to the health of people and animals in case of leakage of dangerous substances and other extraordinary events [38].

According to the conditions for use, sorbents must meet certain criteria in order to be used, in particular:

- universality,
- good sorption capacity,
- storability,
- ecological disposal,
- price.

After all these provisions, when it is found that the sorbent material meets all the criteria and standards, it is included in the use for firefighters [34].

Firefighting units in Slovakia most often have loose sorption material:

- Vapex;
- Hydrophobic loose sorbent LITE-DRY;
- REOSORB;
- ECO-DRY;
- Absodan Plus;
- Spilkleen Plus.

Vapex (Figure 1):

- Hydrophobized perlite is loose and granular.
- Solid fabric with a white-gray tinge.
- It binds the adsorbent to its surface.
- It is used for the sorption of oil substances.
- It can be used on water surfaces and solid surfaces.
- The disadvantage is its dustiness.
- Volumetric weight: 180 kg/m³.
- Composition—rock of volcanic origin 69%, SiO₂ 18%, Al₂O₃ 6%, CaO + MgO 4%, Na₂O + K₂O, 3%, Fe₂O₃ [39,40].



Figure 1. Vapex (source: elaborated by authors).

LITE-DRY (Figure 2):

- Hydrophobic loose sorbent
- Fast absorption
- It is not dusty
- Low weight and high sorption capacity
- It is made from recycled cellulose
- Absorbs chemicals, oil and water, petroleum products
- The colour is dark grey
- Absorbs from the water surface and solid surface [41].

REOSORB (Figure 3):

- Defined as, sorption grit. Made of polypropylene fibre and fabric
- High sorption capacity
- It is used for aggressive liquids, using chemical sorption
- Disadvantage of use in windy weather
- The colour is yellow
- Weight: 5 kg

- Volume: 70 L
- It is disposed of by burning
- Ingestion on water surfaces, where it can float on the water surface. Used also on solid surfaces [42].



Figure 2. LITE DRY (source: elaborated by authors).

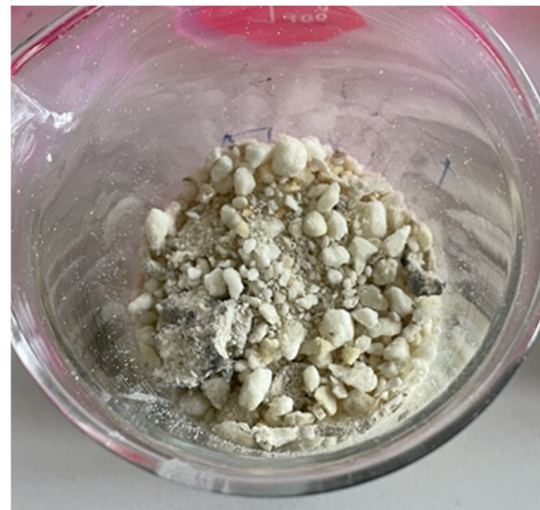


Figure 3. REOSORB (source: elaborated by authors).

ECO-DRY (Figure 4):

- Universal loose sorbent, which is made of non-combustible diatomaceous earth
- It is used for oil products that leak on a solid surface
- The shape remains the same after saturation and does not change
- Low dustiness, and does not release the soaked liquid
- It is disposed of by storage
- Weight: 10 kg
- Volume: 17 L
- Colour: yellow-brown [43].

Absodan plus (Figure 5):

- Created from calcined Moler
- Colour: reddish brown
- Liquidation takes place on storage
- It is defined as with fast absorption and low dustiness
- Universal loose sorbent
- The soaked substance remains inside the absorbent

- Liquids, oils, fats, petroleum substances, and some chemicals
- Used on a solid surface
- Weight: 10 kg
- Volume: 17–20 L [44].



Figure 4. ECO-DRY (source: elaborated by authors).



Figure 5. Absodan plus (source: elaborated by authors).

Spilkleen Plus (Figure 6):

- Made from cellulose and China clay
- Universal loose sorbent
- Colour: brown
- Possibility of liquidation by storage
- Cleans oil products, coolants from roads
- Minimal burden on the environment
- Replacement for Vapex
- Weight: 10 kg
- Volume 17 L [45].



Figure 6. Spinkleen (source: elaborated by authors).

2.2. Brief Characteristics of Operating Fluids

The operating fluids, examined in this article, are most often used to drive vehicles, processed oil being used. Traffic accidents are often accompanied by the phenomenon of operating fluid leaking onto the road, and it is necessary to prevent its leakage and remove the danger. The most common operating fluids in traffic accidents include oil, diesel fuel, gasoline, coolant, and oil–gasoline mixtures [46,47].

Diesel fuel (Figure 7)—mixture that is produced from crude oil by distillation and hydrofining. It is made up of hydrocarbons. It may contain additives, which contribute to its quality and change its chemical composition. It is used to run diesel engines. The colour is yellowish and has an oily consistency. It becomes slippery when in contact with a solid surface (road). The viscosity of diesel, which is measured at 20 °C, ranges from 2.5 to $5 \times 10^{-6} \text{ m}^2 \cdot \text{s}^{-1}$. The density of diesel fuel measured at 20 °C, depending on its composition, varies between 0.8 and $0.88 \text{ kg} \cdot \text{dm}^{-3}$. Mass fraction of carbon is $87\% \text{ kg} \cdot \text{kg}^{-1}$. The flash point is 56 °C, the ignition temperature is 215 °C, and the calorific value of a stoichiometric mixture with air is $3433 \text{ kJ} \cdot \text{m}^{-3}$. It is defined as a flammable liquid III hazard class with flash point of 55 °C [48,49].



Figure 7. Diesel, gasoline, coolant, engine oil, oil + gasoline (source: elaborated by authors).

Diesel EFECTA (B7), produced by Slovnaft, was used for the research.

Gasoline (Figure 7)—unleaded automobile gasoline with ethanol content. Gasoline is obtained from crude oil by distillation and refinement and used for combustion engines. The colour is yellow, with a significant odour, insoluble in water, and forming an explosive mixture with air. When in contact with water, it creates a thin layer on the surface that sticks to the surface. The viscosity of gasoline at 20 °C is $7.04 \times 10^{-6} \text{ m}^2 \cdot \text{s}^{-1}$. The density of gasoline fuel at 20 °C is $0.751 \text{ kg} \cdot \text{dm}^{-3}$, specific heat is $2.06 \text{ kJ/kg} \cdot \text{K}$, and classified as a flammable liquid of danger class I with flash point of -24 °C [50,51].

EFECTA 95 (E10) gasoline, manufactured by Unipetrol, was used for the research.

Engine oil (Figure 7)—mixture of mineral or synthetic oils. It is used as a lubricant during engine operation. It is produced by functional distillation. The colour is yellowish-

brown, and it has a viscous property. It does not mix with water and floats on the surface. It creates a slippery layer on the road. The kinematic viscosity at 100 °C is 14.0 mm²/s, pour point is −33 °C, flash point is 237 °C, and relative density is approx. 0.885 g/cm³.

ORLEN Oil Platinum Classic Mineral 15W-40 was used for the research.

Coolant (Figure 7)—used to transfer heat from the unit to the cooling centre. It is miscible with water and dangerous for the environment. Composed of monoethylene glycol with organic corrosion inhibitors. The density is 1.119 g/cm³, freezing point (50% vol. in water) −38 °C, boiling point 172 °C, and viscosity at −15 °C is 1.927×10^{-6} m²·s^{−1}. The viscosity at −30 °C is 5.444×10^{-6} m²·s^{−1}. It has different colours, red, and pink, purple, yellow, and blue [52,53].

The coolant used for the research was G12, −37 °C.

A mixture of oil and gasoline (Figure 7)—used for the operation of two-stroke engines and hand-held motor equipment, which are used in manual operation. The characteristics are identical to gasoline and oil, as together they form a mixture. They are mixed in a certain ratio [54].

We can define these substances as adsorbates or absorbates. It depends on which sorbent is used and whether it will absorb the given liquid.

2.3. Methodological Procedure According to the ASTM F726-06 Standard

The testing of sorbent bulk materials used in firefighting units was performed by short-term adsorption performed on service fluids using ASTM F726-06. “Standard Test Method for Performance of Sorbent”.

This test method covers laboratory tests that describe the performance of adsorbents in removing non-emulsified oils and other floating, immiscible liquids from the surface of water. The adsorbent material is tested using established standard tests for factors relating to storage, while specially developed tests are used for covering other performance factors. Oil and water adsorption strength, buoyancy, and reusability tests are included among these latter tests.

Testing was carried out in laboratory conditions with measurements, linked to laboratory tests where adsorbents used on adsorbates, were evaluated.

This method evaluates and examines the maximum sorption capacity; therefore, it is necessary that the adsorbate be of the necessary thickness so that the adsorbent can saturate its entire volume. Under normal conditions, the adsorbent does not come into contact with the thickness of the adsorber in order to be fully saturated. For this reason, the research was carried out according to certain established conditions.

The determination of the test is of the optimal capacity of the adsorbent, without the presence of water.

According to the standard, loose sorbents are defined as type II adsorbents. The conditions of sorbents for research are as follows:

The operating liquid that is used should have a layer of 2.5 cm if the size of the adsorbent placed in the container is smaller than 2.5 cm.

If the adsorbent exceeds 2.5 cm in thickness, then the adsorbent and the tested liquid must have the same layer and thickness.

The sorbent sample should weigh at least 4 g.

Conditioning is carried out of the adsorbent sample, temperature 23 ± 4 °C, relative humidity approx. 70%, by placing in the environment, without covering.

General testing procedure:

1. The adsorbent sample is first weighed.
2. The necessary layer of operating liquid, determined by the conditions, is poured onto the place of adsorption.
3. The weighed sorbent is poured into the container containing the operating liquid. It must float freely, in the position in the test vessel.
4. The time codified for petroleum products and chemicals is 15 ± 20 s. During this time, the sorbent is allowed to form a bond with the operating fluid.

5. After the end of the adsorption, the adsorbent with the soaked liquid is poured through the sieve and allowed to drip for 30 ± 3 s. For oils, the draining time is 15 min.
6. The captured adsorbent is then transferred to a container, where the remaining liquid can still be released, and the final weight is determined.
7. The value is recorded.
8. From the values before and after adsorption, the increase in weight, sorption capacity, and subsequently absorbency are calculated using their relation.
9. All tests are performed 3 times to calculate average values.

Determination of values for research: the sorbents had the same initial mass of 10 g and the height of the sorbed liquid was 4 cm (volume 200 mL).

The research was carried out in the laboratory of the Faculty of Mining, Ecology, Process Control and Geotechnologies of Technical University of Košice, which was provided for the purposes of research for the practical part.

Use of aids:

- Low beakers 400–600 mL with spout (Figure 8), from SIMAX[®], $d = 80$ mm, $h = 110$ mm,
- mesh sieves > 1 mm, from Fisher Slovakia,
- plastic containers, volume—0.5 L, weight—0.1 kg, outer length—230 mm, outer width—180 mm, outside height—40 mm,
- laboratory balance KERN PCB 300-3, maximum weight capacity—360 g, weighing accuracy—0.001 g, diameter 82 mm,
- stopwatches Fisherbrand[™] Tracable[™] Jumbo-Digit Stopwatch, digital stopwatch, $7.62 \times 6.35 \times 2$ cm,
- pharmacy spatula, stainless steel, with hook, volume 100 mL, 140×75 mm, total length 230 mm.



Figure 8. Beakers used in research (source: elaborated by authors).

3. Results

3.1. Increase in Mass of Bulk Sorbent Materials

Procedure according to ASTM F726-06:

1. Weigh the sorbent.
2. The height of the sorbed liquid must be at least 2.5 cm. A height of 4 cm (200 mL) was used.
3. Sorbent is immersed for 15 min.
4. After saturation, it is allowed to drip for 30 s, oils for 15 min.
5. Weigh the soaked sorbent.
6. Determine the weight gain.

Weight gain is according to the formula:

$$S_s = S_{st} - S_0 \quad (1)$$

where,

S_s —weight increase (g).

S_{st} —weight of the adsorbent sample at the end of the test (g).

S_0 —initial weight of dry sorbent (g).

Diesel fuel

Adsorbents on diesel fuel increased their weights differently (Table 1). The REOSORB sorbent increased its weight the best (Figure 9), and was able to increase the weight up to six times. In doing so, it demonstrated that the adsorbent can receive a sufficiently large amount of leaking liquid on its surface. Absodan, Spilkleen, and Ecodry sorbents had relatively the same absorbed amount of liquid per volume. They demonstrated a low ability to increase their volume on diesel fuel. Vapex proved its effectiveness sufficiently, increasing its weight after soaking in diesel oil up to almost five times.

Table 1. Increasing the weight of sorbents (diesel) (source: elaborated by authors).

Diesel Fuel (200 mL)	S_0 (g)	S_{st} (g)	S_s (g)
LITE-DRY	10	24.80	14.80
VAPEX	10	58.54	48.58
REOSORB	10	77.58	67.58
SPILKLEEN PLUS	10	19.15	9.15
ABSODAN PLUS	10	21.71	11.71
ECO-DRY	10	22.74	12.74



Figure 9. REOSORB immersed in diesel and after adsorption and dripping (source: elaborated by authors).

Coolant

On the cooling liquid (Table 2), the ECO-DRY sorbent increased its weight the most. It was able to increase it almost twice, which defines it as the most effective coolant according to the increase in weight, and it was able to receive the most liquid for its pore volume. Vapex and Reosorb also held up well, Spilkleen increased its weight the least.

Table 2. Increasing the weight of sorbents (coolant) (source: elaborated by authors).

Coolant (200 mL)	S_0 (g)	S_{st} (g)	S_s (g)
LITE-DRY	10	18.37	8.37
VAPEX	10	23.89	13.89
REOSORB	10	25.07	15.07
SPILKLEEN PLUS	10	17.97	7.97
ABSODAN PLUS	10	20.81	10.81
ECO-DRY	10	27.18	17.18

Gasoline

Table 3 shows that REOSORB, which received five times its weight from the operating fluid, increased its weight the most. Another increase occurred with VAPES, where it was almost four times. It took the least amount of ABSODAN PLUS into its weight.

Table 3. Increasing the weight of sorbents (gasoline) (source: elaborated by authors).

Gasoline (200 mL)	S_0 (g)	S_{st} (g)	S_s (g)
LITE-DRY	10	20.36	10.36
VAPEX	10	46.80	36.80
REOSORB	10	63.97	53.97
SPILKLEEN PLUS	10	16.49	6.49
ABSODAN PLUS	10	16.17	6.17
ECO-DRY	10	17.77	7.77

Engine oil

The increase in weight shows (Table 4) that REOSORB and VAPEX received the most liquid in their pores. Spilkleen in this case, completely fell behind the others and received only half its weight, which is completely negligible.

Table 4. Increasing the weight of sorbents (coolant) (source: elaborated by authors).

Gasoline (200 mL)	S_0 (g)	S_{st} (g)	S_s (g)
LITE-DRY	10	25.48	15.48
VAPEX	10	58.86	48.86
REOSORB	10	75.99	65.99
SPILKLEEN PLUS	10	15.85	5.85
ABSODAN PLUS	10	20.16	10.16
ECO-DRY	10	23.87	13.87

Mixture of gasoline and oil

In the mixture of gasoline and oil, Vapex was the most suitable, which received the most weight for its volume (Table 5).

Table 5. Increasing the weight of sorbents (mixture of gasoline and oil) (source: elaborated by authors).

Gasoline (200 mL)	S_0 (g)	S_{st} (g)	S_s (g)
LITE-DRY	10	19.37	9.37
VAPEX	10	48.69	38.69
REOSORB	10	47.55	37.55
SPILKLEEN PLUS	10	17.55	7.55
ABSODAN PLUS	10	18.6	8.56
ECO-DRY	10	17.68	7.68

3.2. Sorption Capacity of Sorbents

The sorption capacity of sorbents is an expression of the amount of adsorbed substance on the surface of the sorbent, which increases its volume and weight [55].

It is given in weight units (g/g), which indicates the capture of pollutants as long as the sorption capacity is not exhausted.

Procedure is according to ASTM F726-06:

1. Weigh the sorbent.
2. The height of the sorbed liquid must be at least 2.5 cm. A height of 4 cm (200 mL) was used (Figure 10).
3. Sorbent is immersed for 15 min.
4. After saturation, it is left to drip for 30 s, the oils for 15 min.
5. Weigh the soaked sorbent.



Figure 10. Measuring diesel fuel and determining the initial weight of the sorbent (source: elaborated by authors).

The determination of the sorption capacity was according to the following equation:

$$A = \frac{m_a - m_n}{m_n} \quad (2)$$

where,

A —Sorption capacity (g/g).

m_a —weight of adsorbent after soaking (g).

m_n —mass of dry sorbent (g).

It follows from the values (Table 6) that the Vapex sorbent has the best sorption capacity for the mixture of oil and gasoline. This sorbent generally proves that its sorption capacity on petroleum operating fluids is high. Its sorption capacity did not achieve high efficiency for the cooling liquid, where the value was significantly lower than for the petroleum products.

Table 6. Sorption capacity of sorbents used on operating fluids (source: elaborated by authors).

Sorbent	Sorption Capacity A (g/g)				
	Mixture of Gasoline and Oil	Engine Oil	Diesel	Gasoline	Coolant
LITE-DRY	0.937	1.548	1.48	1.036	0.837
VAPEX	3.869	4.886	4.85	3.68	1.389
REOSORB	3.755	6.599	6.76	5.397	1.507
Spilkleen Plus	0.856	0.585	0.915	0.649	0.797
Absodan Plus	0.856	1.016	1.171	0.617	1.718
ECO-DRY	0.768	1.387	1.274	0.77	1.081

LITE-DRY has an average sorption capacity, but when mixing oil with gasoline, it had a value of 0.937, which does not achieve the average with its subsequent use in practice. Also, it had a significantly low value for the coolant and could not accept sufficient amount of liquid into its pores, and thus its value is low. The highest sorption capacity was demonstrated on motor oil, where the value reached 1.55 g/g. Thus, it accepted 15 g of engine oil for its weight, which increased to 1.5 times its weight. In terms of sorption capacity, it proved its hydrophobicity because it had the lowest sorption capacity for the coolant.

REOSORB, as the only one, had the best sorption capacity on all petroleum operating fluids. Low values, with an absorption time of 15 min. were found only with coolant. Its sorption capacity is the most effective among all sorbents and reaches high numbers for its use in practice.

Spilkleen Plus had below average values and did not achieve high efficiency with any liquid. Its values did not even reach the required average of 1 g/g. Close values with sorption capacity were achieved with diesel fuel, where it was 0.9 g/g. In the evaluation of the sorption capacity, it did not prove its universality.

Absodan Plus surprisingly proved that its highest sorption capacity was on coolant, which was 1.718 g/g. Therefore, it is rather a hydrophilic sorbent that can also absorb water. Of the petroleum products, it was the least able to absorb motor gasoline into its volume and pores. For the others, it had average values, thanks to which it can be classified for use in fire department.

ECO-DRY, in the case of gasoline and mixtures with gasoline and oil, it failed. Its sorption capacity in this case was very low and reached values of 0.77 g/g for gasoline and 0.76 g/g for the mixture. It is not suitable for gasoline spills. Among other operating fluids, it had the highest sorption capacity for oil and was able to absorb almost twice its volume. It proved its universality with its sorption capacity.

Figure 11 shows the process of sorption on engine oil.

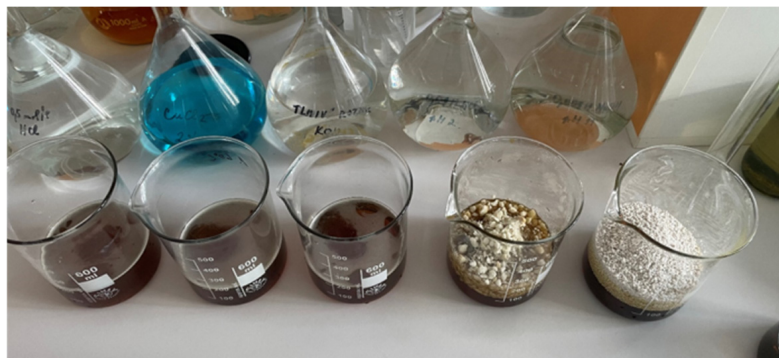


Figure 11. Sorption process on engine oil (source: elaborated by authors).

3.3. Absorbency of Sorbents

Following the determination of the sorption capacity, the absorbency of the sorbents can be determined. We define absorbency as the ability to absorb leaking liquid with a sorbent into the pores and volume. It is given in %. Absorbency of sorbents should be at least 100% to be effective and to be included [56].

Procedure according to ASTM F726-06, for absorbency:

1. Weigh the sorbent.
2. The height of the sorbed liquid must be at least 2.5 cm. A height of 4 cm (200 mL) was used.
3. Immerse sorbent for 15 min.
4. After saturation, it is allowed to drip for 30 s, oils for 15 min.
5. Weigh the soaked sorbent.
6. Determine the weight gain.

The determination of absorbency was according to the following equation:

$$N = \frac{m_a - m_n}{m_n} \times 100 \quad (3)$$

where,

N —absorbency of the sorbent (%).

m_a —weight of adsorbent after soaking (g).

m_n —mass of dry sorbent (g).

From the absorbency values, it is possible to determine whether the sorbents used in firefighting units meet the requirement that the minimum degree of absorbency should be 100%.

Each sorbent on the operating fluid had different output values. For this reason, each sorbent should only be used for substances where its sorption capacity and consequently absorbency are permissible. The values in Table 7 are the output values and subsequently, from these, it can be determined whether the sorbents are satisfactory or not.

Table 7. Absorbency of sorbents on operating fluids (source: elaborated by authors).

Sorbent	Absorbency N (%)				
	Mixture of Gasoline and Oil	Engine Oil	Diesel	Gasoline	Coolant
LITE-DRY	93.7	154.8	148	103.6	83.7
VAPEX	386.9	488.6	485	368	138.9
REOSORB	375.5	659.9	676	539.7	150.7
Spilkleen Plus	85.6	58.5	91.5	64.9	79.7
Absodan Plus	85.6	101.6	117.1	61.7	171.8
ECO-DRY	76.8	138.7	127.4	77	108.1

Suitable for diesel fuel:

- LITE-DRY;
- REOSORB;
- Vapex;
- Absodan Plus;
- ECO-DRY.

Suitable for petrol/oil mixture:

- Vapex;
- REOSORB.

Suitable for engine oil:

- LITE-DRY;
- REOSORB;
- Vapex;
- Absodan Plus;
- ECO-DRY.

Suitable for gasoline:

- LITE-DRY;
- REOSORB;
- Vapex (Figure 12).

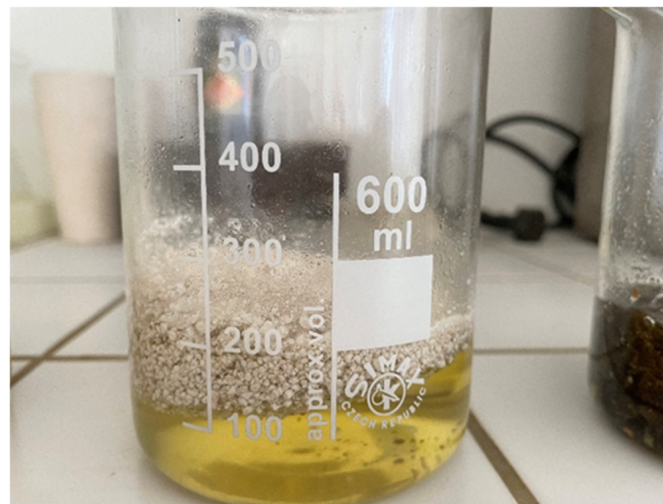


Figure 12. Vapex sorption process with motor gasoline (source: elaborated by authors).

Suitable for coolant:

- REOSORB;
- Vapex;
- Absodan Plus;
- ECO-DRY.

Spilkleen Plus did not comply with even one operating fluid, because its values did not reach at least 100%.

3.4. The Time Factor of Sorbents from the Point of View of Visualization

The adsorbents behaved and sorbed differently during the sorption, which took place on operating liquids for a set time of 15 min. Each sorbent bound the liquid differently to its volume. The time factor of sorbents from the point of view of visualization was evaluated from the initial immersion of the sorbent in the liquid after 5 min and 10 min. After 15 min, the sorbent was completely soaked, and its final appearance and structure were evaluated.

LITE-DRY

Gasoline (Figure 13)—After immersing in gasoline, it immediately sank to the bottom and its colour changed to black. Over 5 and 10 min, it did not change and remained settled at the bottom of the test chamber.



Figure 13. LITE-DRY immersed in gasoline and after draining (source: elaborated by authors).

After dripping, it did not change its shape and its colour became black. The liquid held fast to its surface.

Coolant—After pouring into the test chamber, it stayed on the surface of the coolant and did not dive down. After 5 min it partially submerged. At 10 min, almost its entire volume was immersed in liquid. Subsequently, it was able to absorb the liquid in its entire volume. After dripping, it became darker but was dry.

Oil and gasoline mixture—Upon contact with the mixture, it sank to the bottom and immediately began to absorb to its volume. It did not change over further time. It remained at the bottom of the test container. After dripping, its colour was dark and it was wet. The texture remained.

Engine oil—After pouring into the test container, the oil fell to the bottom, causing the oil to change colour to dark orange blue. It stayed on the bottom of the container the whole time. After dripping, it became black and its texture became oily. It had oil on its parts, which was visible but dripping and it created a thick mixture.

Diesel fuel—After immersion, it sank to the bottom where it adsorbed. From a visual point of view, it changed the colour of diesel to yellow blue. During the entire adsorption, it was located at the bottom. After dripping, it became black, and its structure was unchanged. It sucked the liquid into its volume which did not stick to the surface of the sorbent.

VAPEX

Gasoline—After immersion, it sank to the bottom and absorbed. It did not submerge any of its entire volume in the liquid and stayed on the surface. The colour did not change. After dripping, it remained dry and formed a cluster of granules.

Diesel fuel—It stayed on the surface and after about 7 min started to sink but was still afloat. After dripping, it formed clumps and did not hold the diesel in its volume.

Mixture of oil and gasoline—It kept afloat and gradually sank. It could not submerge its entire volume in the liquid. After dripping, it had a red tint and formed clumps of granules.

Engine oil (Figure 14)—It soaked in gradually. The part that was submerged turned yellow. It gradually sank to the bottom. After dripping, it became a clump and hardened. It had a yellowish colour and did not release the absorbed liquid.



Figure 14. Vapex immersed in engine oil and after draining (source: elaborated by authors).

Coolant—It stayed afloat. During the entire period of adsorption, it did not dive under, but was still able to absorb liquid from the surface into its volume. It had a pink tinge after dripping. Certain parts were wet and they formed clumps and the rest remained loose.

REOSORB

Gasoline—After being poured into the test container, it stayed on the surface for the first few minutes. Gradually it began to sink to the bottom. During the whole adsorption, it kept its shape, and the structure of the crumb started to become wet. After dripping, it remained yellow, but its shape was unchanged. It created a wet mixture.

Engine oil—It gradually sank into the oil. It took about 7 min as long as it dived under. It stayed afloat but its entire volume was wet. After dripping, the colour changed to yellow, and it became solidier. It kept its substance after soaking.

Coolant (Figure 15)—It stayed afloat and did not sink to the bottom. It soaked the material from the surface and did not change during the period of operation. After dripping, balls were formed that were attached to each other. It kept the fabric on its surface.

Diesel fuel—It immersed three quarters of its volume in the liquid. For 12 min, it stayed just below the surface. The shape remained as before sorption, but the colour changed to yellow. It gradually released the trapped liquid from suction.



Figure 15. REOSORB with coolant and after draining (source: elaborated by authors).

Mixture of oil and gasoline—It stayed afloat and gradually sank. It could not immerse its entire volume in the mixture of oil and gasoline. After dripping, it soaked up the wetness, had a red tint, and formed clusters of granules.

Spilkleen Plus, Absodan Plus, ECO-DRY

These sorbents had identical properties in the absorption time factor and also in visualization.

Gasoline—When it came into contact with gasoline, it sank to the bottom. After 5 min it started to form a layer on the surface which was about 2 mm thick and light brown in colour. After dripping, its colour darkened compared to the original. The formed clusters and sorbents became wet. It adsorbed from the beginning of immersion.

Engine oil—For 1 min, it immersed its entire volume in the liquid, where it stayed at the bottom. After 5 min. it started to form a foamy white layer on the surface, which remained on the surface until re-sieving. After dripping, it darkened and created a runny mixture that was wet and spilled out.

Coolant—After pouring, it automatically sank to the bottom of the test container, where adsorption took place. During the 15 min, its properties and the properties of the liquids did not change. After dripping, it formed a stiffer mixture. The fabric remained intact and did not drip.

Oil and gasoline mixture—During adsorption for 10 min, it formed a layer on the surface. Later it fell to the bottom. After dripping, the colour of the sorbent darkened.

Diesel fuel—It fell into the liquid and sank to the bottom. It gradually changed the colour of diesel to yellow-orange. After soaking and dripping, clumps were formed that were darker in colour than before they started. They were soaked but their soaked liquid was gradually released.

Figure 16 shows Absodan, Spilkleen, and ECO-DRY immersed in gasoline and ECO-DRY after dripping.



Figure 16. Absodan, Spilkleen, and ECO-DRY immersed in gasoline and ECO-DRY after dripping (source: elaborated by authors).

3.5. Removal of Sorbents from Local Roads

Because of frequent traffic accidents, operating fluids can leak onto the road (roadway). Firefighters prevent the leakage of operating fluids into the environment on roadways by using sorbent materials that capture the leaked fluid. After using sorbents, the soaked sorbents must be collected and then removed from the road. During removal, the removal of sorbents and leaked liquid is monitored so that dirt and sorbent residues do not remain on the road.

In this section, the selected bulk sorbents, which had to be removed, were evaluated. With loose sorbents, which have small, structured granules and particles, it happens that the sorbent becomes caught on the road where there are pores and it is then difficult to remove it. In this case, removal is difficult and leaves behind a minimal amount that can represent a secondary threat to the environment. Liquid-soaked sorbent is also considered a hazardous material.

In the practice of research, observation, and the possibility of removal, two groups of sorbents were created (Figure 17):

1. Easily removable—this group included sorbent grit and hydrophobic loose sorbent. Their advantage was that they could be easily removed from the road, using the means of collection—LITE-DRY left a trace with engine oil, REOSORB, in turn, left a minimal trace of diesel fuel.
2. Difficult to remove—the remains of the soaked sorbent was left on the road, which represented a secondary threat. During the collection, small amounts had to be collected on brooms and shovels.

Easily removable

- LITE- DRY
- REOSORB

Difficult to remove

- Vapex
- Spillkleen Plus
- Absodan Plus
- ECO-DRY

Figure 17. Distribution of sorbents from the point of view of removal (source: elaborated by authors).

The division of sorbents into individual groups according to removability was carried out on the basis of a practical test for individual sorbents using the technical means used by firefighters (Figure 18).

When removing sorbents from the road, the following means are used:

- Scraping—broom, shovel, rake.
- Collection and storage—barrels, containers, tubs, tanks, sieves, buckets.

Subsequently, after removal, it is necessary to choose an appropriate disposal procedure. Because the sorbent becomes a dangerous material after being soaked with the substance, it is also necessary to use an ecological disposal procedure, which must be taken into account so that no danger arises.

During removal and subsequent storage for disposal, the used and absorbed sorbent must be sufficiently wrapped, marked, and placed to prevent its leakage.

Types of liquidation:

- Combustion—a physico-chemical process where at high temperatures compounds are decomposed into basic elements. From the point of view of the environment, this is a safe way of removing hazardous substances.
- Biogradation—oil and organic pollution is broken down. It takes place in a humid environment with access to air. A long-term process where ploughing and shifting are

practiced. If the dangerous substance concentration drops below the set standard, the material can be used for final storage.



Figure 18. Leaked operating fluids on the road and their backfilling using sorbents (source: elaborated by authors).

4. Discussion

It is necessary to pay more attention to the difference in absorption with G12, compared to petroleum products. G 12 is a water-dilutable liquid, but petroleum products do not mix with water. Also, for this reason, it is necessary to distinguish individual sorbents according to their properties and ability to absorb or adsorb the dangerous substance, which are also used for the individual results when comparing sorbents.

In the mentioned study, it was necessary to take into account that during extraordinary events in traffic, leakage of operating fluids does not occur separately, but in a certain mixture. The ratio of these fluids is different in every traffic accident depending on variables such as the type of vehicle, the type of operating fluids, the amount of fluid in the tank, the speed at which the vehicle hits an obstacle, and also, the surrounding climatic conditions. There are many external factors, and individual mixtures are consequently different, where the sorbent used for the said mixtures will also behave differently.

It should be noted that sorbents such as Vapex, REOSORB, Splinkleen Plus, ECO-DRY, and LITE-DRY achieved excellent sorption capacity for operating fluids, unlike Abdosan Plus sorbent. However, Abdosan Plus outperformed these sorbents emphatically for the cooling liquid. The best level of absorption capacity of sorbents on operating fluids was achieved the best level with Abdosan Plus as a coolant.

Similar results, carried out worldwide, also confirm the mentioned results for petroleum products, where products based on vermiculite, zeolite, silica rocks, and various commercial forms achieved satisfactory results. The substance Moler raw material is more effective than these sorbents for the cooling liquid [57–63].

It is therefore appropriate for subsequent research to state precisely the individual mixtures of oil-based operating fluids with coolant that must be studied and incorporated into more in-depth research. The stated results for individual ratios are currently absent in research results.

Teas, C. et al. (2001) recorded results for the absorbency of expanded perlite, where the values, similar to those in this paper, were from 2 to 3.5 g/g of sorbent. Such values were also recorded in the presented study with Vapex (expanded perlite). Also, many researches regarding sorbents and sorbents have been carried out on sorption capacity, absorbency, weight of absorbent substances, volume of sorbents, such as Hakami, et al. (2020), Hyung-MIn, et al. (1992), Gupta, et al. (2017), Nwadiogbu, et al. (2016), where

similar results were achieved for individual sorbents. However, it should be emphasized that too much research has had little attention devoted directly to cooling liquid. It is the results from this article that show different results for the individual characteristics of these sorbents for the case of cooling liquid compared to the case of petroleum products. It is this dangerous substance which constitutes part of the escape of products during extraordinary events and, according to its composition, is considered particularly dangerous for the human body and the environment [64–68].

5. Conclusions

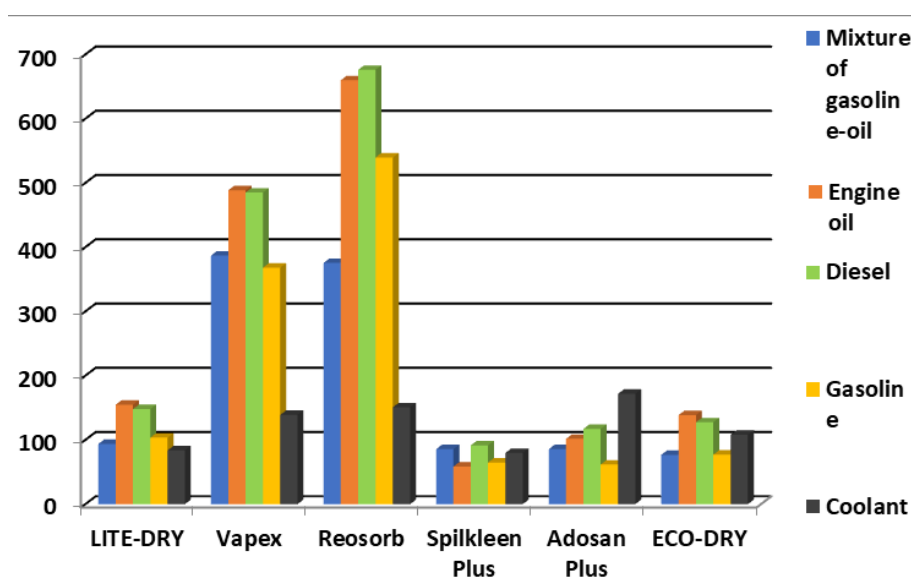
From the evaluation of the sorbents itself, it can be concluded that the most effective sorbent evaluated was REOSORB. This type of sorbent had high absorbency on motor oil, diesel, and gasoline. Its absorbency reached up to 676% in engine oil. This value was well in excess of 100%. From the results, it can be concluded that the mentioned sorbent was the most effective.

Vapex, which has been used for a long time in fire departments, also had a high sorption efficiency. It achieved high efficiency for all operating fluids. The highest absorbency was achieved with a mixture of oil with gasoline, engine oil, and diesel. This is important from the point of view of fire brigades, as these liquids are most often used in accidents. The values were in the range of 368–488%. Similar to REOSORBA, Vapex also reached the lowest values for coolant. REOSORB appears to be of better quality for use in liquidation of dangerous substance leaks in traffic accidents, as Vapex is dusty, its consumption is high in adverse weather.

As for coolant leakage, Absodan Plus achieved the best results. Its absorbency achieved up to 171%, which was much higher than other materials.

The least effective sorbent was Splinkleen Plus, which did not achieve the absorption limit of 100%. After conducting the laboratory test, it did not succeed in either case. Its values were in the range of 77%. It is therefore unsuitable for use in firefighting units, and it is necessary to consider removing it from the firefighter's equipment. This sorbent has not proven to be an adequate substitute for any sorbent used in fire departments.

Graph 1 shows the absorbency of individual sorbents according to the results in %.



Graph 1. Absorbency of sorbents on operating fluids in % (source: elaborated by authors).

The research shows that the decisive factor for sorbents in firefighting units is absorbency, i.e., increase in weight and sorption capacity.

In the case of evaluation, there is also an absorption/adsorption time. In practice, the most important time to leave the sorbents to absorb/adsorb the liquid is 15 min. By this time, most of the sorbents are saturated with absorbate/adsorbate.

Their structure is important for removing used sorbents from the surface. In the removal evaluation, LITE-DRY and REOSORB had the highest efficiency. Their composition is textile, and their particles are larger compared to other sorbents.

From the overall evaluation of the sorbents used by firefighting units, REOSORB and Vapex have the most effective sorption capacity and other evaluated factors. For practical purposes, it would be advisable to secure them for all firefighting units in sufficient quantity.

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