PAPERS

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EXPERIMENTAL STUDY OF THE COMPOSITE PARTS OF THE LIGHT-BEAM ATTENUATION PROCESS IN THE WATERS OF THE GULF OF GDAŃSK *

Contents: 1. Introduction, 2. The methods and scope of ments, 3. The results of the investigations, 4. Summary and conclusions; Streszczenie; References.

1. INTRODUCTION

The attenuation of light in sea water is brought about by the processes of absorption and scattering by molecules of water and sea salt, organic, matter dissolved in the water, and a complex set of suspended particles [9]. The contribution of these substances in the processes of absorption and scattering varies throughout different water media and depends much on the spectral band of light waves considered [10, 12]. Quantitative data on this contribution are sparse in bibliographical sources [9, 10]. Thorough investigation of this phenomenon in certain marine areas is a prerequisite for the development of appropriate models and forecasts as to the supply and transfer of solar energy in the sea, as well as for the application of sensitive optical methods in the remote measurement and monitoring of changes in the water medium. A knowledge of the composite parts of the light attenuation process and their correlations enables the optical monitoring of water pollution, insight into sediment transport, conditions of primary production, analysis of the macrostructure of water masses, optimization of the use of underwater phototechnical devices, intepretation of aerophotography, etc.

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* Some results of this study were presented at the IAPSO/IAMAP Symposium „Ocean Optics" held during the 16th General Assembly of the International Union of Geodesy and Geophysics in Grenoble, 1975 [4].

These possibilities of the application of optics in the exploration of the Baltic waters were taken into account among other factors when, in 1972, the joint Polish—German hydro-optical studies were initiated under the programme of multilateral research of the CMEA member countries. Several survey cruises and coastal experiments were conducted in the years 1972—1975. Apart from other aspects, these studies have enabled us to collect statistical data for the components of light-beam attenuation processes in the waters of the Gulf of Gdańsk. These data and their interpretation are the subject of this article. The objective of this work is to reveal the statistical correlations between the light absorption and scattering, together with the contribution of individual groups of sea water components to these processes. The relationships are of a local character, in our case they illustrate the situation in the fairly shallow Gulf of Gdańsk and adjacent Baltic waters, where the waters of the Vistula estuary, as well as the sea bottom and coastal dynamics exert a strong influence.

2. THE METHODS AND SCOPE OF MEASUREMENTS

Complex hydrooptical and physico-chemical measurements were carried out on board the research vessel "Professor Albrecht Penck" (Academy of Sciences of the GDR) at drift stations.

The light absorption was measured in situ with the complete set of four basic irradiance meters. The coefficient of absorption was found from the law of conservation for radiant energy:

$$\operatorname{div} \vec{E} = -a E_o \qquad (2.1)$$

where: E_o — the scalar irradiance,
$\vec{E}$ — the vector irradiance,
a — the total absorption coefficient.

Assuming the model of horizontally stratified sea [9] and the stationarity of the light field during the measurements, from Eq. 2.1 one obtains the following formula for the absorption coefficient at the depth z:

$$a(z) = \frac{1}{E_o(z)} \frac{d}{dz} [E_d(z) - E_u(z)] \qquad (2.2)$$

This formula was used in the computations. E_d and E_u are the downwelling and upwelling irradiance, respectively. The irradiances $E_d(z)$, $E_u(z)$, and $E_o(z)$ were measured with irradiance meters fitted with light collectors [3], photomultipliers, and interference filters. All irradiance meters were intercalibrated; each was permitted to function with a maximum relative error of 1 per cent.

Simultaneous with the *in situ* absorption measurements, water samples of several litres were taken from respective depths (1 to 40 m); they were submitted to precise laboratory analysis on board. The total attenuation coefficient c in the samples was measured with the aid of a "Specol" type, two-beam photometer adjusted to 50 cm long measuring cells. The measurements were made in the examined water samples, with reference to clear distilled water. By this means the values $(c - c_w)$ were obtained for water samples tested, c_w being the total beam attenuation coefficient for pure water. At the same time some water from each sample (1 litre) was thoroughly filtered through membrane filters with 0.1-micrometer pore diameter and at underpressures of 0.4 to 0.7 at. The residues on the filters were employed to determine the dry mass of suspended matter in the samples, and the filtrate was also analyzed thoroughly with the aid of the "Specol" photometer mentioned above. The values of the beam attenuation coefficient (related to the pure water) for the samples without suspended matter were obtained from such measurements. For the Baltic waters this coefficient can be well identified with the absorption coefficient of "yellow substance" a_y [11].

On the basis of the values of a, a_y, and $(c - c_w)$ measured and taking into account that the values of c_w for pure water are known and relatively small in our case [2], one can determine the remaining components of the beam attenuation from simple relationships, viz:

— the total scattering coefficient $b = c - a$
— the particle attenuation coefficient $c_p = c - c_w - a_y$
— the particle absorption coefficient $a_p = a - a_y - a_w$
— the particle scattering coefficient $b_p = c_p - a_p$.

Three light wavelengths of 425 nm, 525 nm, and 725 nm (with respective interference filters) were used for these statistical studies.

Other quantities measured simultaneously (of which not all have been discussed in this paper) include the particle size distribution function determined by the Coulter counter [15], the light scattering function in vitro at angles of 45° and 90°, chlorophyll a, b, c contents and the contents of organic carbon both in water and in suspended particles [3].

3. THE RESULTS OF THE INVESTIGATIONS

The investigations made it possible to determine empirical correlations between respective coefficients of absorption and scattering; the method of least squares was employed to approximate the correlations. The results found in the Gulf of Gdańsk waters during various seasons over four years indicate that the correlations are linear. Thus, the linear approxi-

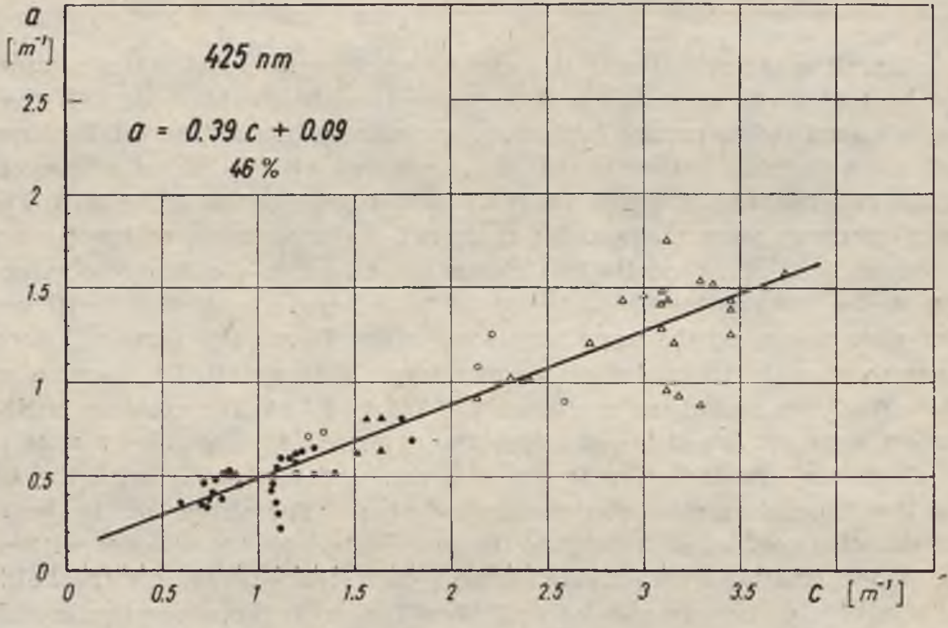

Fig. 1. Correlation between the total absorption coefficient, a, and the total attenuation coefficient, c, for the 425 nm wavelength. The correlation indicates the contribution of absorption in the total attenuation of a parallel light beam. The notation accepted here and in further diagrams provides the following information:

— wavelength of analyzed light,

— empirical formula for the linear approximation of the correlation, which describes the relationship drawn (by the method of least squares),

— mean ratio of the quantities on the ordinate axis (y) to the abscissa quantities (x) in per cent, i.e. in this case, mean percentage of absorption in the total attenuation $< \frac{a}{c} > = 0.46 = 46\%$,

— months and years in which investigations were conducted, four individual points being inserted in the diagram:

▲ June 1972 ○ June 1973 ● September 1973 □ September 1974 △ March 1975

Ryc. 1. Korelacja pomiędzy całkowitym współczynnikiem absorpcji, a, i całkowitym współczynnikiem osłabiania, c, dla światła o długości fali 425 nm. Korelacja ta wyraża udział absorpcji w całkowitym osłabieniu równoległej wiązki światła. Oznaczenia na rysunku (jak również na dalszych rysunkach zamieszczonych w tej pracy) opisują odpowiednio:

— długość fali badanego światła,

— wzór empiryczny będący liniowym przybliżeniem korelacji i opisujący przebieg wykreślonej zależności (wg metody najmniejszych kwadratów),

— średni stosunek wielkości na osi rzędnych (y) do wielkości na osi odciętych (x), wyrażony w procentach, tj. średni procentowy udział w tym przypadku absorpcji w całkowitym osłabieniu $\left(< \frac{a}{c} > = 46\%\right)$,

— miesiące i lata, w których prowadzono badania i ustalono poszczególne punkty na wykresie:

▲ czerwiec 1972 ○ czerwiec 1973 ● wrzesień 1973 □ wrzesień 1974 △ marzec 1975 mation has been accepted in all cases, which can be seen in the diagrams and empirical formulae.

Let us start the review of these results from the relationships for violet light in the band around the 425 nm wavelength. Fig. 1 shows the dependance of the total absorption coefficient a on the total attenuation coefficient c. This relationship illustrates the contribution of absorption in the total attenuation, its linear approximation being as follows:

$$a_{425} = (0.39 \pm 0.03)\, c_{425} + (0.09 \pm 0.05) \tag{3.1}$$

where the coefficients a and c are expressed in m^{-1}.
The other numerical values in the brackets depict the standard deviations, which will also be given in the following formulae.

The contribution of the total scattering in the overall attenuation is shown analogously in Fig. 2. The linear approximation of this relationship is given by the formula:

$$b_{425} = (0.61 \pm 0.03)\, c_{425} - (0.09 \pm 0.05) \tag{3.2}$$

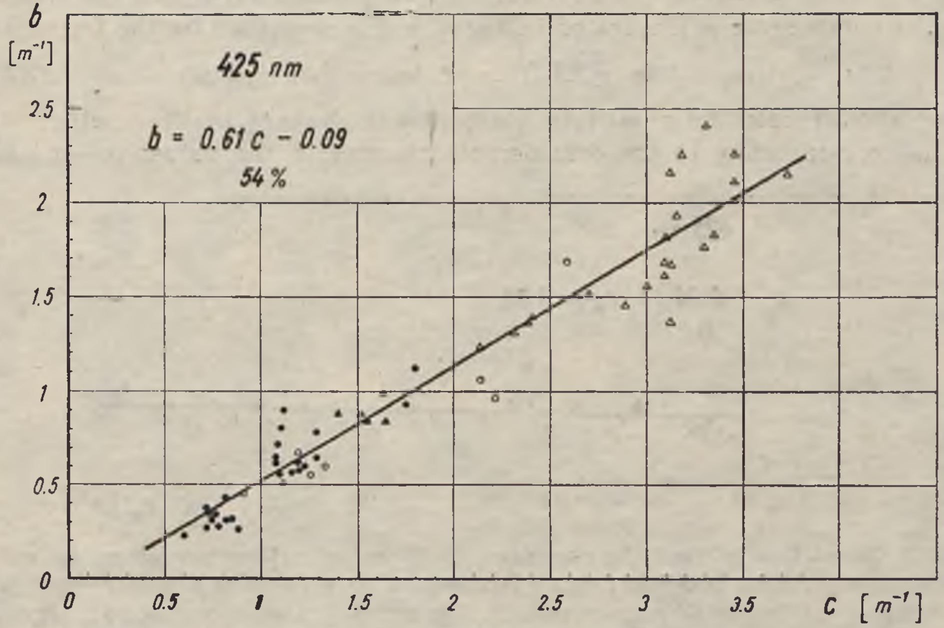

Fig. 2. Correlation between the total scattering coefficient, b, and the total attenuation coefficient, c, for the 425 nm wavelength. The correlation indicates the part played by scattering in the total attenuation of a parallel beam of light. Notation as in Fig. 1

Ryc. 2. Korelacja pomiędzy całkowitym współczynnikiem rozpraszania, b, i całkowitym współczynnikiem osłabiania, c, dla światła o długości fali 425 nm. Korelacja ta wyraża udział rozpraszania w całkowitym osłabieniu równoległej wiązki światła. Oznaczenia jak na ryc. 1

The mean ratios $\langle \frac{a}{c} \rangle_{425}$ and $\langle \frac{b}{c} \rangle_{425}$ computed independently from individual measurements are 0.46 and 0.54, respectively, which can be put as 46 percent mean statistical contribution of the absorption in the total light attenuation in the 452 nm wavelength band, while the remaining 54 per cent of the attenuation in the waters investigated should be attributed to scattering.

Let us now consider the contrubution of attenuation, absorption and scattering of sea water components, as related to the attenuation caused by all components (with the exclusion of water molecules), i.e. $(c - c_w)$. From among all the components we will distinguish two groups, i.e. dissolved yellow substance and suspended particles, which are of primary importance to the light attenuation spectrum in the band of visible waves and which diversify the optical properties of sea waters. The effect of salinity and other substances contained in sea water on its optical properties is basically negligible in the visible range.

The role of the yellow substance in the attenuation by all the water on its components is illustrated in Fig. 3 and is described by the formula:

$$a_{y,425} = (0.04 \pm 0.02)\,(c - c_w)_{425} + (0.30 \pm 0.02) \tag{3.3}$$

One should note the relatively insignificant changes in the coefficient $a_{y,425}$ corresponding to the considerable changes in the values $(c - c_w)_{425}$

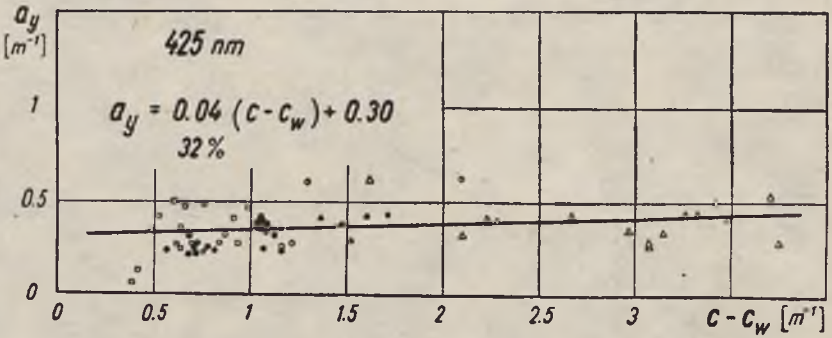

Fig. 3. Correlation between the absorption coefficient of yellow substances, a_y, and the total attenuation coefficient of all components both dissolved and suspended in water $(c - c_w)$ for the 425 nm wavelength. The correlation describes the part played by the absorption of the yellow substances in the attenuation of the parallel beam of light by all components of sea water (water itself excluded) Notation as in Fig. 1

Ryc. 3. Korelacja pomiędzy współczynnikiem absorpcji substancji żółtych, a_y, i sumarycznym współczynnikiem osłabiania wszystkich zawartych w wodzie składników rozpuszczonych i zawieszonych $(c - c_w)$ dla światła o długości fali 425 nm. Korelacja ta wyraża udział absorpcji substancji żółtych w osłabianiu równoległej wiązki światła przez wszystkie zawarte w wodzie morskiej składniki (z wyłączeniem udziału samej wody). Oznaczenia jak na ryc. 1

measured in the water area studied. This fact indicates the major effect of suspended particles on the considerable time-and-space differentiation of the light-attenuation properties of these waters. This is illustrated directly in Fig. 4, where the attenuation caused by suspended particles is shown against the background of the attenuation due to all components of the water studied. The latter relationship is well described by the following empirical formula:

$$c_{p,425} = (0.96 \pm 0.02)\,(c - c_w)_{425} - (0.30 \pm 0.02) \qquad (3.4)$$

From the data measured it also follows that 68 per cent of the light attenuation (425 nm) due to all sea water components in Gdańsk Bay

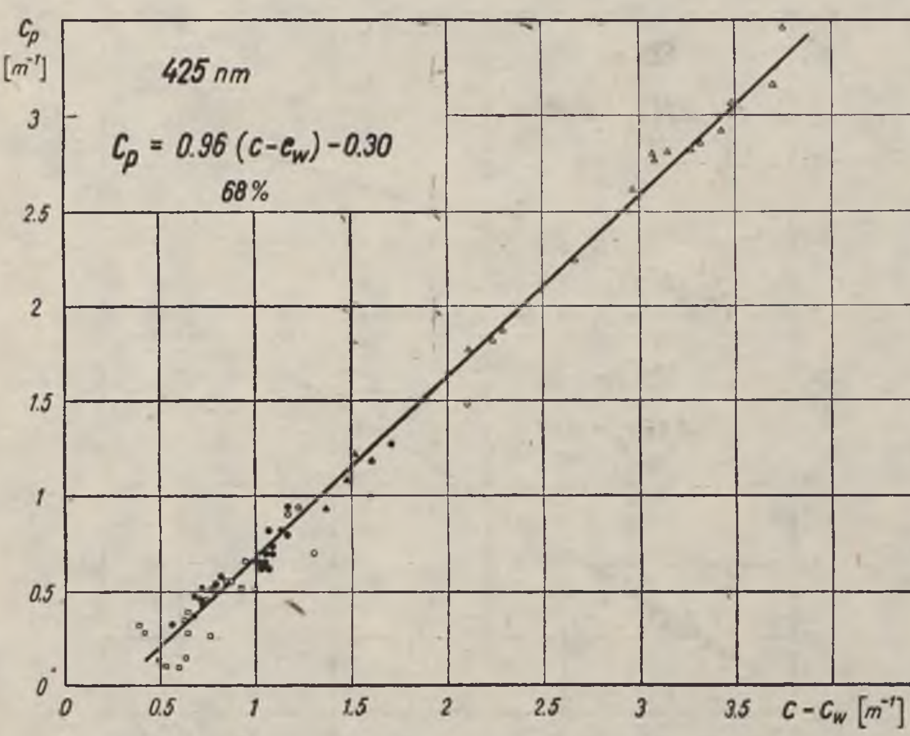

Fig. 4. Correlation between the particles attenuation coefficient, c_p, and the attenuation coefficient of all components dissolved and suspended in the water ($c - c_w$) for the 425 nm wavelength. This correlation illustrates the share of the attenuation due to particles in the attenuation of a parallel beam of light caused by all sea water components (water itself exluded). Notation as in Fig. 1

Ryc. 4. Korelacja pomiędzy współczynnikiem osłabiania zawiesin, c_p, i sumarycznym współczynnikiem osłabiania wszystkich zawartych w wodzie składników rozpuszczonych i zawieszonych ($c - c_w$) dla światła o długości fali 425 nm. Korelacja ta wyraża udział osłabiania przez zawiesiny w osłabianiu równoległej wiązki światła przez wszystkie zawarte w wodzie morskiej składniki (z wyłączeniem udziału samej wody). Oznaczenia jak na ryc. 1

should be attributed to the effect of suspended particles as a statistical mean value, in spite of the large quantity of yellow substance dissolved in the waters.

The effect of suspended particles on light attenuation can in turn be distinguished from the scattering by particles and the absorption by these particles. The results of analysis of these two components given by the empirical formulae

$$a_{p,425} = (0.34 \pm 0.03)\, c_{p,425} - (0.08 \pm 0.45) \qquad (3.5)$$

$$b_{p,425} = (0.66 \pm 0.03)\, c_{p,425} + (0.08 \pm 0.05) \qquad (3.6)$$

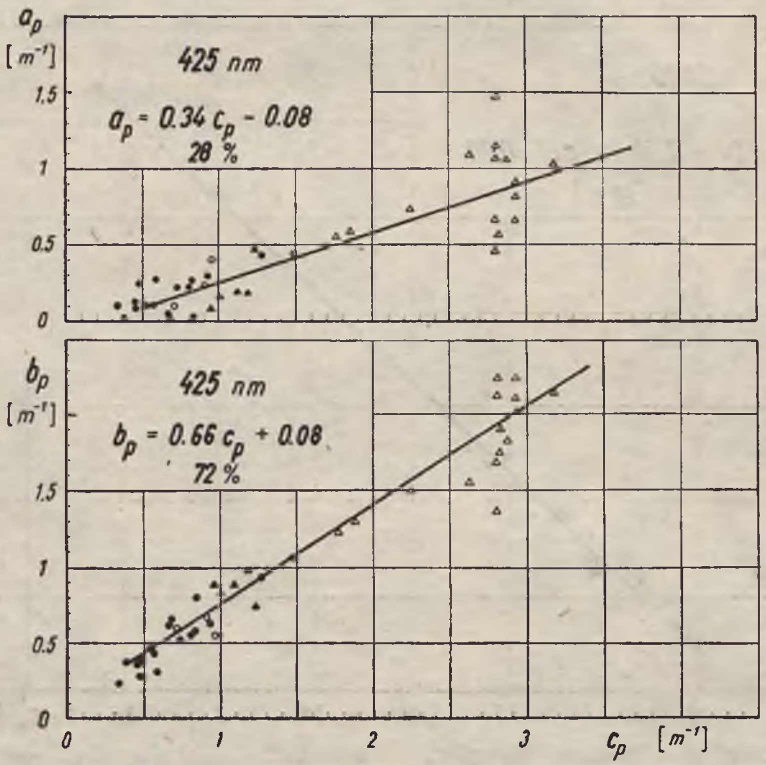

Fig. 5. Correlation between the particles absorption coefficients, a_p, and the particles scattering coefficient, b_p, versus the particles attenuation coefficient, c_p, for the 425 nm wavelength. The correlations depict the part played by both absorption and scattering due to suspended particles in the attenuation of a parallel beam of light by these particles. Notation as in Fig. 1

Ryc. 5. Korelacja pomiędzy współczynnikami absorbcji zawiesin, a_p, oraz rozpraszania na zawiesinach, b_p, i współczynnikiem osłabiania zawiesin, c_p, dla światła o długości fali 425 nm. Korelacje te wyrażają odpowiednio udział absorpcji zawiesin i rozpraszania na zawiesinach w osłabianiu równoległej wiązki światła przez zawiesiny. Oznaczenia jak na ryc. 1

are also illustrated in Fig. 5. The mean ratio $\left\langle \frac{a_p}{c_p} \right\rangle_{425}$ is 0.28. This figure (28 per cent of attenuation of particles) can be attributed to the light absorption caused by suspended particles (for $\lambda = 425$ nm) under mean statistical conditions, while the remaining 72 per cent is caused by scattering, even though, as can be deduced from the diagram, this finding seems to be very rough, as no changes in the composition and properties of suspended particles sets in time and space have been taken into consideration.

Let us now pass to the results of similar analyses for the two remaining wavelengths tested, i.e. 525 nm and 725 nm, for which the effect of yellow substance is known to be considerably less pronounced than that of violet light. The 525 nm band in the attenuation spectrum is contained in the minimum attenuation spectral range of the Baltic waters [8], while the substantial increase in the light attenuation around 725 nm follows primarily from the absorptional properties of water molecules. The part of absorption and scattering in the total light attenuation in the 525 nm band is illustrated in Figs. 6 and 7 on the basis of the results obtained, while the linear empirical relationships are the following:

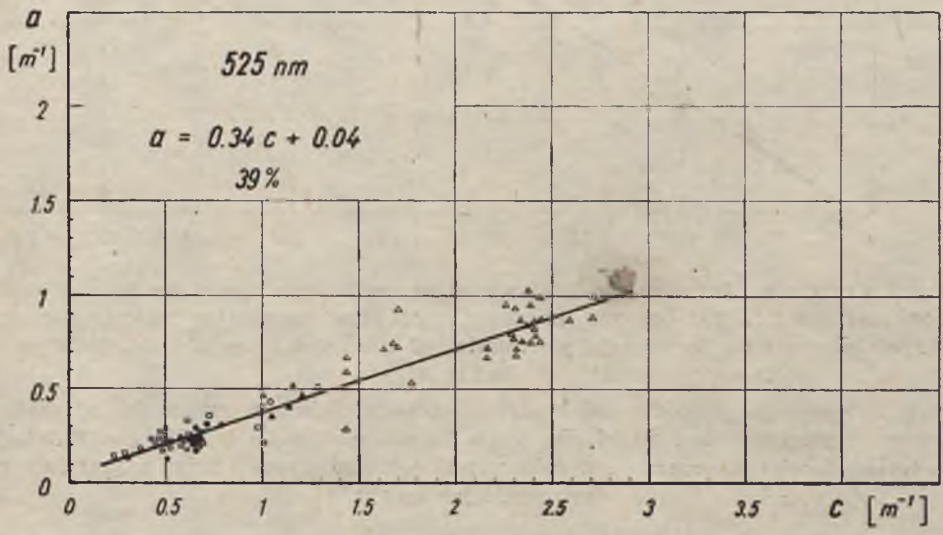

Fig. 6. Correlation between the total absorption coefficient, a, and the total attenuation coefficient, c, for 525 nm wavelength. The correlation describes the part played by absorption in the total attenuation of a parallel beam of light. Notation as in Fig. 1

Ryc. 6. Korelacja pomiędzy całkowitym współczynnikiem absorpcji, a, i całkowitym współczynnikiem osłabiania, c, dla światła o długości fali 525 nm. Korelacja ta wyraża udział absorpcji w całkowitym osłabianiu równoległej wiązki światła. Oznaczenia jak na ryc. 1

$$a_{525} = (0.34 \pm 0.01)\, c_{525} + (0.04 \pm 0.02) \tag{3.7}$$

$$b_{525} = (0.66 \pm 0.01)\, c_{525} - (0.04 \pm 0.02) \tag{3.8}$$

From this data it also appears that the mean statistical ratios $\left\langle \frac{a}{c} \right\rangle_{525}$ and $\left\langle \frac{b}{c} \right\rangle_{525}$ are 0.39 and 0.61, respectively, which is equivalent to 39 per cent light beam total attenuation due to the total absorption (in the 525 nm band and in the water area investigated).

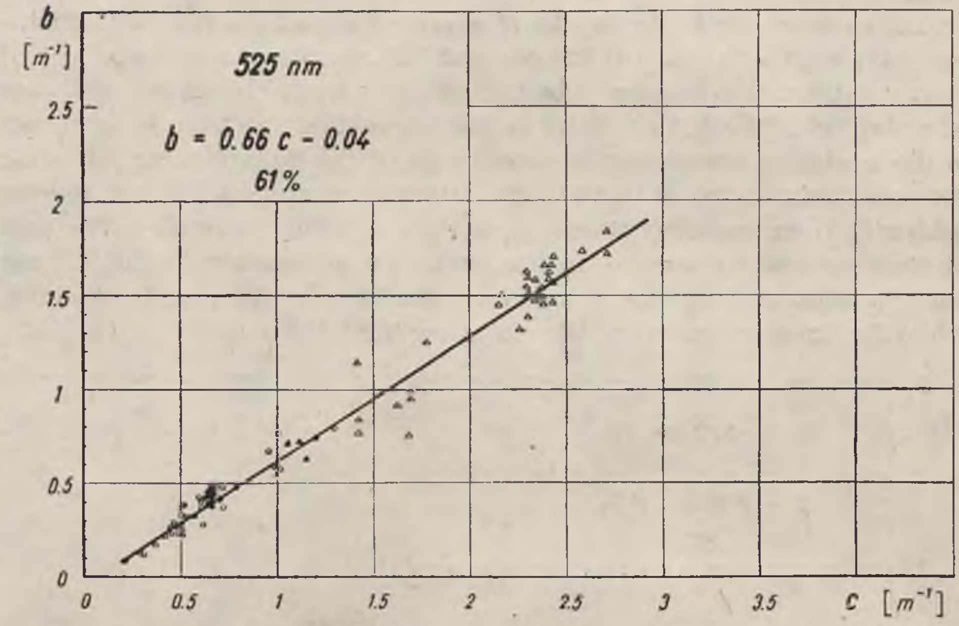

Fig. 7. Correlation between the total scattering coefficient, b, and the total attenuation coefficient, c, for the 525 nm wavelength. The correlation reflects the part played by scattering in the total attenuation of a parallel beam of light. Notation as in Fig. 1

Ryc. 7. Korelacja pomiędzy całkowitym współczynnikiem rozpraszania, b, i całkowitym współczynnikiem osłabiania, c, dla światła o długości fali 525 nm. Korelacja ta wyraża udział rozpraszania w całkowitym osłabianiu równoległej wiązki światła. Oznaczenia jak na ryc. 1

The portion of the attenuation in the 525 nm band caused by suspended particles alone is illustrated in Fig. 8. The diagram shows almost perfect linear correlation between the attenuation caused by all water components $(c - c_w)_{525}$ and the attenuation due to suspended particles $c_{p,525}$. This pronounced linear relationship given by the formula

$$c_{p,525} = (1.00 \pm 0.01)\,(c - c_w)_{525} - (0.08 \pm 0.01) \tag{3.9}$$

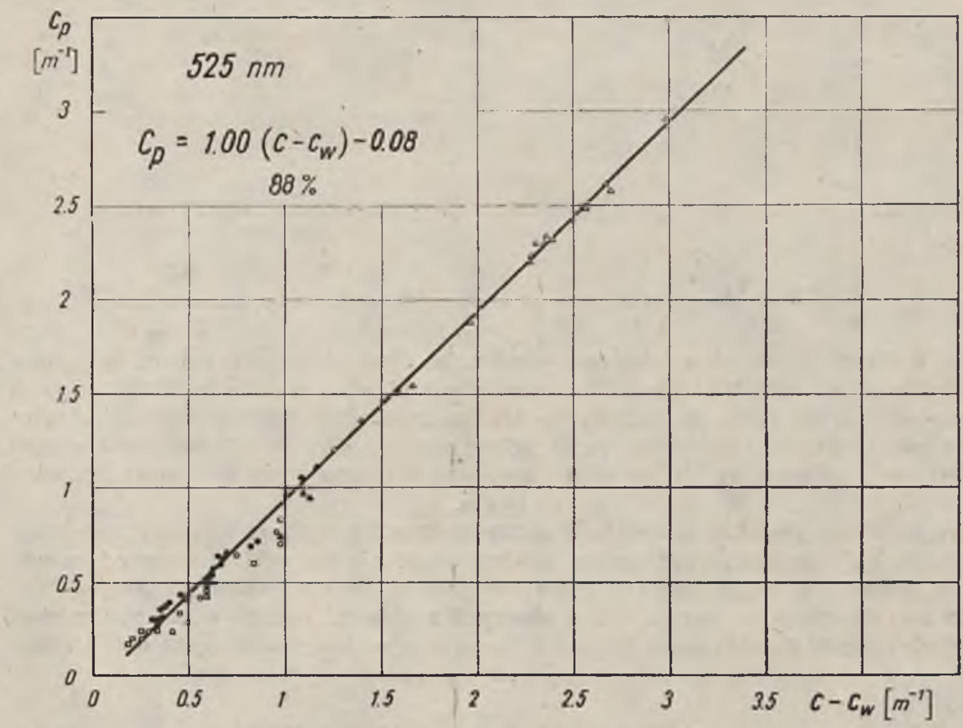

Fig. 8. Correlation between the particles attenuation coefficient, c_p, and the attenuation coefficient of all components dissolved and suspended in water ($c - c_w$) for the 525 nm wavelength. The correlation expresses the part played by particle induced attenuation of a parallel beam by all the components of the sea water (with the exception of water itself). Notation as in Fig. 1

Ryc. 8. Korelacja pomiędzy współczynnikiem osłabiania zawiesin, c_p, i sumarycznym współczynnikiem osłabiania wszystkich zawartych w wodzie składników rozpuszczonych i zawieszonych ($c - c_w$) dla światła o długości fali 525 nm. Korelacja ta wyraża udział osłabiania przez zawiesiny w osłabianiu równoległej wiązki światła przez wszystkie zawarte w wodzie morskiej składniki (z wyłączeniem udziału samej wody). Oznaczenia jak na ryc. 1

is most probably due to the fact that the mean statistical contribution of suspended particles in the attenuation is as much as 88 per cent, while the absorption by the yellow substance a_{y525} does not exceed 12 per cent on average and does not indicate a clear growth trend with increasing attenuation coefficients measured (cf. Fig. 9).

The part played by absorption and scattering in the 525 nm light attenuation by suspended particles is illustrated in Fig. 10.

The respective linear approximations of these relationships are the following:

$$a_{p,525} = (0.35 \pm 0.02)\, c_{p,525} - (0.05 \pm 0.03) \qquad (3.10)$$

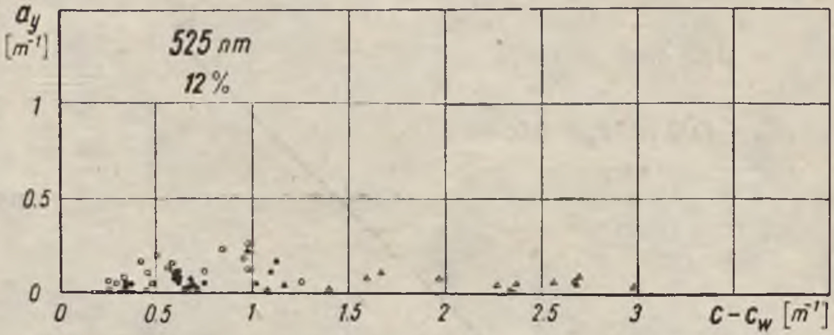

Fig. 9. Result of the correlation analysis for the absorption coefficient of the yellow substance, a_y, and the attenuation coefficient of all components dissolved and suspended in sea water ($c - c_w$) for the 525 nm wavelength. The correlation indicates the part played by the absorption by yellow substance in the attenuation of a parallel beam of light by all sea water components (water itself excluded). Notation as in Fig. 1

Ryc. 9. Wynik poszukiwań korelacji pomiędzy współczynnikiem absorpcji substancji żółtych, a_y, i sumarycznym współczynnikiem osłabiania wszystkich zawartych w wodzie składników rozpuszczonych i zawieszonych ($c - c_w$) dla światła o długości fali 525 nm. Korelacja ta wyraża udział absorpcji substancji żółtych w osłabianiu równoległej wiązki światła przez wszystkie zawarte w wodzie morskiej składniki (z wyłączeniem udziału samej wody). Oznaczenia jak na ryc. 1

$$b_{p,525} = (0.65 \pm 0.02)\, c_{p,525} + (0.05 \pm 0.03) \tag{3.11}$$

The standard deviations found here are relatively considerable because of the errors inherent in this band, where the absolute values of the absorption coefficient are fairly low.

With the considerable scatter of the test data considered it appeared that the contribution of absorption of the suspended particles in the total attenuation of particles in the 525 nm band is 28 per cent on average, which is identical as in the 425 nm band.

Concluding the above considerations about the components of the light beam attenuation process it is worthwhile noting the ideal linear relationship for $c_{p,725} = f\,(c - c_w)_{725}$ in red, shown in Fig. 11. The formula:

$$c_{p,725} = (0.98 \pm 0.01)\,(c - c_w)_{725} - (0.03 \pm 0.01) \tag{3.12}$$

describes this relationship accurately. From independent computations it also follows that, again in mean statistical terms, 89 per cent of the attenuation caused by all water components in the 725 nm band should be attributed to the suspended particles. Because of the low absorption capacity of the water components in this band, as compared with the high absorption of the water itself, the absorption and scattering on particles were not analyzed separately, as this approach would have considerable errors due to the measuring techniques applied.

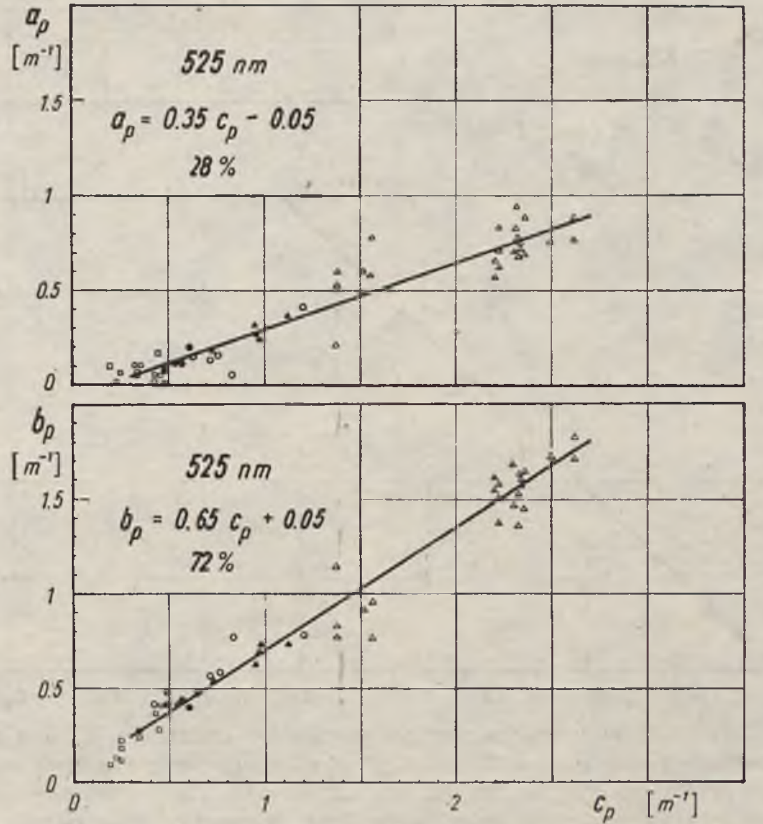

Fig. 10. Correlations between the particle absorption coefficient, a_p, also the particle scattering coefficient, b_p, and the particle attenuation coefficient, c_p, for the 525 nm wavelength. The correlations describe the part played by particle absorption and particle scattering on the attenuation of parallel light beams by suspended particles. Notation as in Fig. 1

Ryc. 10. Korelacje pomiędzy współczynnikami absorpcji zawiesin, a_p, oraz rozpraszania na zawiesinach, b_p, i współczynnikiem osłabiania zawiesin, c_p, dla światła o długości fali 525 nm. Korelacje te wyrażają odpowiednio udział absorpcji zawiesin i rozpraszania na zawiesinach w osłabianiu równoległej wiązki światła przez zawiesiny. Oznaczenia jak na ryc. 1

In view of the prevailing effect of suspended particles on the light attenuation in the waters studied, a good correlation between the concentration of particles in water and certain attenuation could be expected. Unfortunately, the concentration of suspended particles can be expressed only through their dry residue in a unit volume of water, through the number of suspended particles of a given size etc. These parameters do not reflect the physical character of suspended particles and thus must not be clearly correlated with the light attenuation coefficients. How-

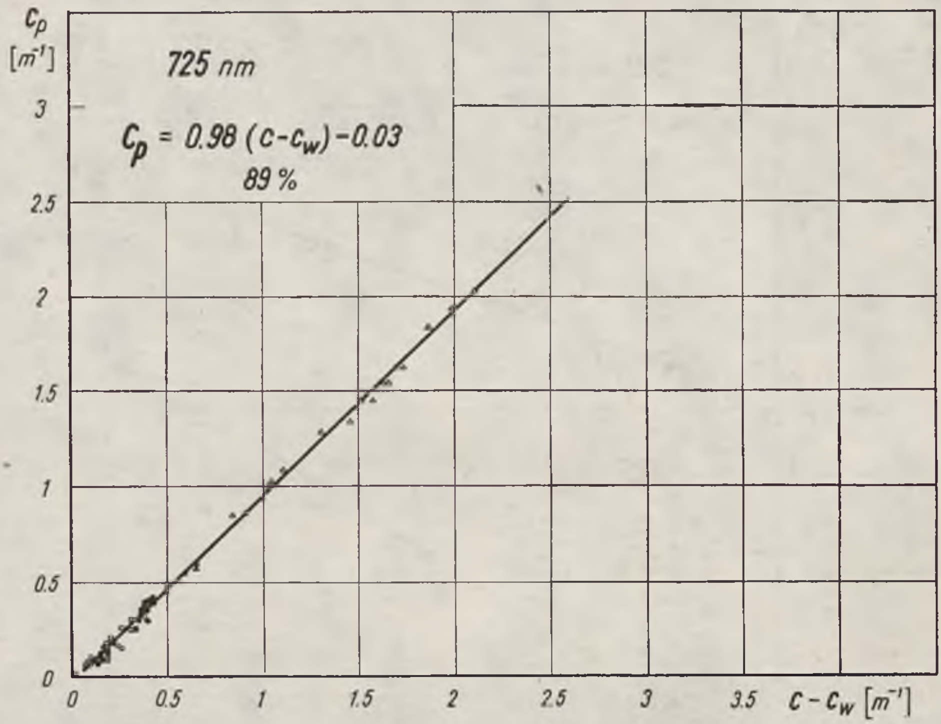

Fig. 11. Correlation between the particle attenuation coefficient, c_p, and the attenuation coefficient associated with the effect of all components dissolved and suspended in sea water ($c - c_w$) for the 725 nm wavelength. The correlation reflects the part played by suspended particles in the total attenuation of a parallel beam of light by all sea water components (water itself excluded). Notation as in Fig. 1

Ryc. 11. Korelacja pomiędzy współczynnikiem osłabiania zawiesin, c_p, i sumarycznym współczynnikiem osłabiania wszystkich zawartych w wodzie składników rozpuszczonych i zawieszonych ($c - c_w$) dla światła o długości fali 725 nm. Korelacja ta wyraża udział osłabiania przez zawiesiny w całkowitym osłabianiu równoległej wiązki światła przez wszystkie zawarte w wodzie morskiej składniki (z wyłączeniem udziału samej wody). Oznaczenia jak na ryc. 1

ever, the dry mass of suspended matter in 1 litre of water is a quantity of particular practical importance, and it is therefore most frequently correlated with the light attenuation properties of sea water [5, 6, 14].

Analyzed in this study was the correlation between the particles attenuation coefficient and the dry mass of particles. Empirical relationships are obtained (Fig. 12), their linear approximations for three wavelengths being respectively:

$$c_{p,425} = (0.15 \pm 0.01)m_p + (0.61 \pm 0.08) \quad (3.13)$$

$$c_{p,525} = (0.12 \pm 0.01)m_p + (0.47 \pm 0.06) \quad (3.14)$$

$$c_{p,725} = (0.09 \pm 0.01)m_p + (0.25 \pm 0.04) \quad (3.15)$$

where: m_p — dry mass of suspended particles in mg, per 1 litre of water,

c_p — the particle attenuation coefficient in m^{-1}.

Irrespective of the above correlations, the mean ratios $\left\langle \frac{c_p}{m_p} \right\rangle$ were also computed. These can be interpreted as the particle mass attenuation coefficients. These mass attenuation coefficients of suspended particles assume the following figures:

$$\left\langle \frac{c_{p,425}}{m_p} \right\rangle = 0.55 \ \frac{m^{-1}}{mg/l}$$

$$\left\langle \frac{c_{p,525}}{m_p} \right\rangle = 0.43 \ \frac{m^{-1}}{mg/l}$$

$$\left\langle \frac{c_{p,725}}{m_p} \right\rangle = 0.25 \ \frac{m^{-1}}{mg/l}$$

From the comparison of these figures it follows that the mass attenuation coefficient of suspended particles decreases considerably with increasing wavelengths.

The scatter of points in the diagram $c_p = f(m_p)$ (similar for all three wavelengths) suggests ambiguous validity of this relationship and results

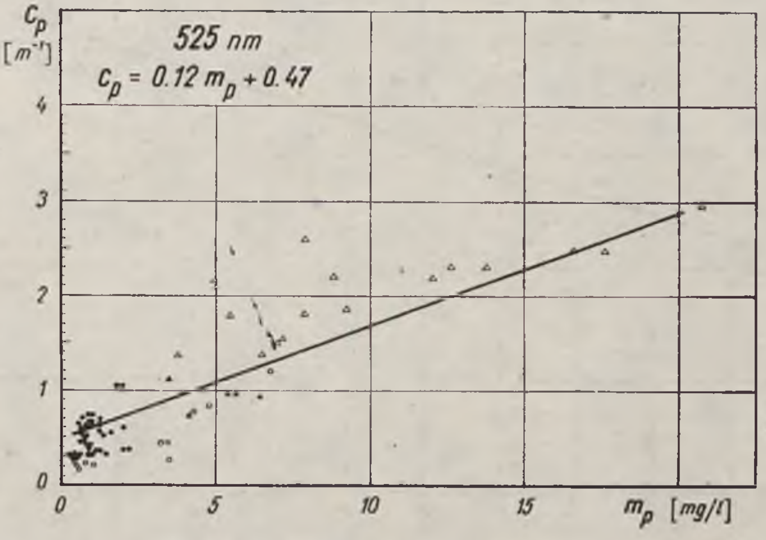

Fig. 12. Correlation between the particle attenuation coefficient, c_p, for the 525 nm wavelength and the concentration of suspended particles in water, m_p, in milligrams of dry mass per litre of water. Notation as in Fig. 1

Ryc. 12. Korelacja pomiędzy współczynnikiem osłabiania zawiesin, c_p, dla światła o długości fali 525 nm i koncentracją zawiesin w wodzie, m_p, wyrażona w miligramach suchej masy na litr wody. Oznaczenia jak na ryc. 1

among other things from the differences in particle size distributions and their density, as shown in [14].

The light absorption by the yellow substance dissolved in sea water depends on their concentration in a given water body. This concentration is well described by the amount of organic carbon C_{org} contained in the water. According to [13], the average mass of organic carbon C_{org} is about one-half of the mass of all organic matter dissolved in the sea and does not deviate much from this figure in individual cases. Of course only a certain portion of this matter contains chromophores characteristic for the yellow substance [1, 11]. The dependence of the absorption of yellow substance on the concentration of organic carbon C_{org} for the 425 nm wavelength studied herein is shown in Fig. 13 and can be approximated by the following empirical formula:

$$a_{y,425} = (0.021 \pm 0.002)\, C_{org} + (0.204 \pm 0.013) \qquad (3.16)$$

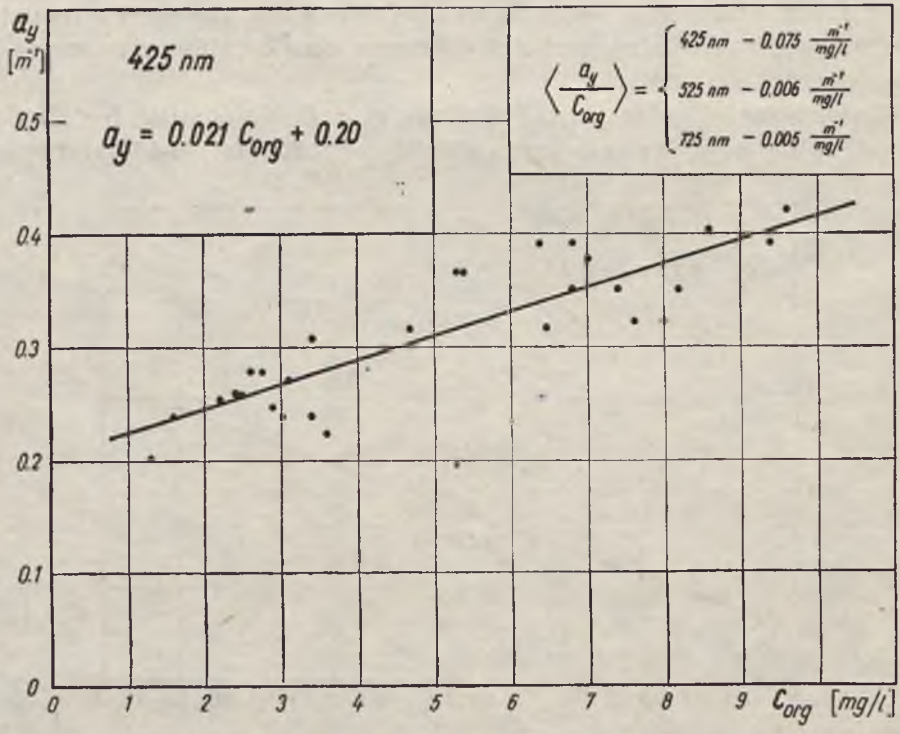

Fig. 13. Correlation between the absorption coefficient of yellow substance, a_y, for the 425 nm wavelength and the concentration of organic carbon in water (in mg per litre), as found from the series of tests in September 1973

Ryc. 13. Korelacja pomiędzy współczynnikiem absorpcji substancji żółtych, a_y, dla światła o długości fali 425 nm i koncentracją węgla organicznego w wodzie wyrażona w mg/l, z serii badań przeprowadzonych we wrześniu 1973 r.

where: a_y is expressed in m^{-1} and C_{org} in mg/l. The relationships $a_y = f\ (C_{ogr})$ for the 525 nm and 725 nm wavelengths do not yield good statistical correlations, which is associated with the low values of the yellow substance absorption coefficient encountered in these two bands of the light spectrum. The characteristic shape of the absorption spectrum of the yellow substance, displaying gradual decrease in the absorption with increasing wavelengths is indicated by the mean mass absorption coefficient of this substance, computed independently for three wavelengths, viz:

$$\left\langle \frac{a_{y,425}}{C_{org}} \right\rangle = 0.075 \frac{m^{-1}}{mg/l}$$

$$\left\langle \frac{a_{y,525}}{C_{org}} \right\rangle = 0.006 \frac{m^{-1}}{mg/l}$$

$$\left\langle \frac{a_{y,725}}{C_{org}} \right\rangle = 0.005 \frac{m^{-1}}{mg/l}$$

The course of the relationship in Fig. 13 shows a clear tendency for the mass absorption coefficient of the yellow substance to decrease with the increasing concentration of organic carbon in the waters studied. This might result from the stronger growth of this organic matter which absorbs visible light less intensively.

4. SUMMARY AND CONCLUSIONS

The results of the investigations presented herein exemplify the contribution of individual components of the process of light beam attenuation in the total attenuation in Gulf of Gdańsk and adjacent Baltic waters, which are the type 2 to 8 of the coastal waters, after Jerlov's classification [9]. Fig. 14 illustrates briefly these contributions. It shows schematically the mean relative contribution of the suspended particles and the yellow substance to the processes of absorption and scattering of individual light wavelengths analyzed, values of the coefficient $(c - c_w)$ being taken as 100 per cent reference level (Fig. 14a). Since the illustration of the light attenuation components in the diagram is self-explanatory we will only call the reader's attention to the little-known fact that the absorption of the suspended particles is quite considerable and amounts to 26 per cent of $(c - c_w)$ in green light. The absorption of the yellow substance displays the anticipated decrease with wavelengths. However, this is observed even in the red band, although it does not affect the total attenuation coefficient in this band much, as can be seen from Fig. 14b, in view of the overwhelming absorption of pure water. The mean absorption of the yellow substances obtained in the red, amouting to 11 per cent of ($c - c_w$) seems to be a bit too high. This can be due to the specific character of the coastal waters studied and because of the possible traces of suspended particles present in the fil-

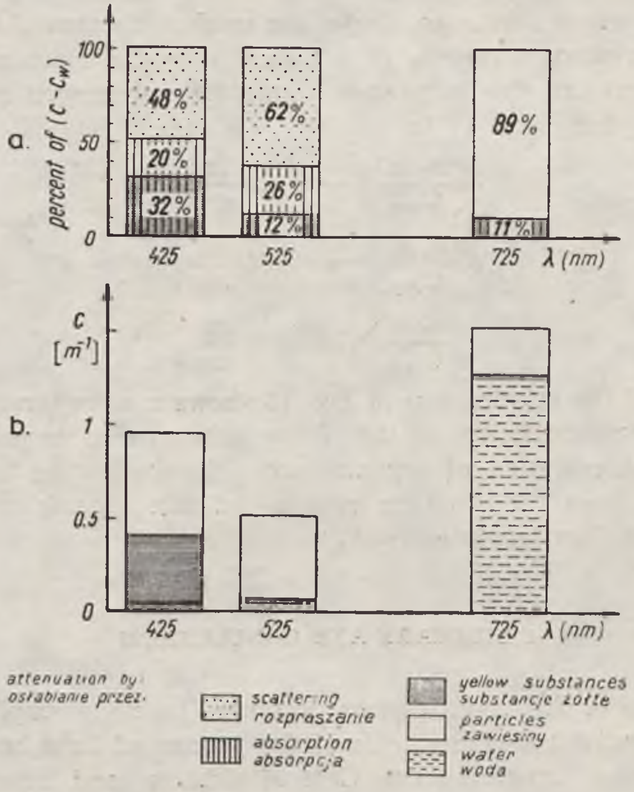

Fig. 14. Illustration of the average contribution of respective components of the attenuation process in the total attenuation of a parallel beam of light, for three wavelengths analyzed:

a. Mean percentage of the absorption and scattering due to suspended particles and yellow subsance.

b. An example of the contribution of the suspended particles, yellow substance, and water in the total attenuation coefficient, for an average sample which contains 5 ml of organic carbon per 1 litre of water and 1 mg of dry mass of particles per 1 litre of water

Rys. 14. Ilustracja średnich udziałów poszczególnych elementów procesu osłabiania w całkowitym osłabianiu wiązki światła dla trzech badanych długości fal świetlnych:

a. Średni procentowy udział absorpcji i rozpraszania przez zawiesiny i substancje żółte.

b. Przykładowy wkład zawiesin, substancji żółtych i wody w całkowity współczynnik osłabiania dla przeciętnej próbki zawierającej węgiel organiczny w ilości 5 ml/l i zawiesiny w ilości 1 mg suchej masy na litr trate samples, for which the light attenuation measured has been identified with the absorption of yellow substances $c - c_w - c_p = a_y$. The effect of suspended traces in the filtrates seems to be less important for shorter waves (425 nm, 525 nm) because of the higher absorption of yellow substances in these bands.

Fig. 14b gives an example of the contribution of suspended particles, yellow substances, and water to the total light attenuation coefficient in an average sample of water with the dry mass of suspended particles $m_p = 1$ mg per litre and 5 mg of organic carbon dissolved in 1 litre of the water.

The results presented for three wavelengths delineate the spectrum of light beam attenuation in the Baltic waters with a characteristic minimum in the band of 500 to 600 nm, also described elswhere [8, 11]. However, first of all one faces the prevailing effect of the suspended particles on the light beam attenuation in the 525 nm band. Therefore, this band seems to be the most convenient for optical measurements of the changes in the concentration of suspended matter in the water areas studied. The difference in the violet and green attenuations can, how ever, serve as a certain indicator of changes in the concentration of yellow substances in water.

The analyzed correlations between the absorption and scattering on the one hand and the total attenuation together with the contribution of individual components in the overall indicators on the other hand, seem to be linear. The empirical linear approximations of these correlations are particularly good in those cases which describe the contribution of the suspended particles in the process of attenuation, even though the differentiation of the physical properties of the suspended particles in space and time has not been demonstrated in this paper. The linearity of the relationships cited holds true in general over a wide range of the attenuation coefficients observed in the waters studied, i.e. from about $c = 0.3\ m^{-1}$ to about $c = 4\ m^{-1}$ for 425 nm. The statistical scatter of individual results noted within this wide range does not imply, however, any relationship other than the linear. Against the background of these considerable changes in the total attenuation coefficient, c, observed in all three wavelength bands tested minor changes in the absorption coefficient of yellow substances a_y, visible in Figs. 3 and 9, are characteristic.

With the change in $(c - c_w)_{425}$ from $0.3\ m^{-1}$ to about $4\ m^{-1}$ the mean value of $a_{y,425}$ increases only slightly from about $0.3\ m^{-1}$ to $0.4\ m^{-1}$, while the maximum values vary from $0.1\ m^{-1}$ to $0.6\ m^{-1}$. It can thus be concluded that the strong variability of the optical properties of the analyzed waters is mainly due to the suspended particles. The considerable changes in the concentration of these particles can be caused by biological activity of plankton in the water body, entrapment of sediments from beach and bottom, variable sediment transport rate from the Vistula river and other tributaries, and varying water circulation. It is therefore important to analyze the quantitative relationships between the parameters which describe the suspended particles and their optical properties together with their effect on the underwater light field. It would also appear worthwhile to extend the statistical investigations to the open Baltic waters. Both these objectives are included in further studies by the Authors and their associates.

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BADANIA DOŚWIADCZALNE ELEMENTÓW SKŁADOWYCH PROCESU OSŁABIANIA ŚWIATŁA W WODACH ZATOKI GDAŃSKIEJ

STRESZCZENIE

W wyniku kompleksowych badań hydrooptycznych podczas rejsów badawczych po Zatoce Gdańskiej i przyległych wodach Bałtyku w latach 1972—1975 ustalono empiryczne liniowe współzależności pomiędzy poszczególnymi elementami składowymi procesu osłabiania światła w wodzie morskiej na przykładzie badanych wód. Wyznaczono średni statystyczny procentowy udział absorpcji i rozpraszania w całkowitym osłabianiu światła oraz oddzielnie udział absorpcji i rozpraszania zawiesin i absorpcji organicznych substancji żółtych w tym procesie. Badania przeprowadzono dla wybranych długości fal światła 425 nm, 525 nm i 725 nm. Znaleziono też wstępnie średnie masowe współczynniki osłabiania zawiesin i średnie masowe współczynniki absorpcji substancji żółtych w przeliczeniu na zawartość masy rozpuszczonego węgla organicznego w wodzie.

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