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Analysis of the fracture surface morphology of concrete by the method of vertical sections

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Abstract. The examinations carried out have confirmed a relationship existing between the character of fracture surfaces and the composition and structure of (basalt and gravel) concretes. For both concretes investigated, a very good correlation was obtained between the profile line development factor, R_L, and the fracture surface development factor, R_S. With the increase in the R_L parameter, the fracture surface development factor R_S also increased. Agreement between the proposed relationship of $R_S = f(R_L)$ and the proposal given by Coster and Chermant (1983) was obtained. Stereological examinations carried out along with fractographic examinations made it possible to obtain a statistical model for the determination of R_L (or R_S) based on the volume of air voids in concrete, V_{air}, the specific surface of air pores, $S_{V_{air}}$ the specific surface of coarse aggregate, $S_{Vagg.}$, and the volume of mortar, V_m. An effect of coarse aggregate type on the obtained values of the profile line development factor, R_L, as well as on the relationship $R_S = f(R_L)$ was observed. The increment in the fracture surface development factor R_S with increasing R_L parameter was larger in basalt concretes than in gravel concretes, which was a consequence of the level of complexity of fractures formed, resulting chiefly from the shape of coarse aggregate grains.

Keywords: concrete; computer analysis; vertical section methods; fractography; stereology.

1. Introduction

One of the sources of information on the mechanism of fracture is the analysis of its effects and, above all, fracture surfaces formed, also known as separation surfaces. From the point of view of quantitative fractography, the fracture is a geometrical form of a complex topography, containing non-uniformly arranged elements of diverse shape and size. The observation of the fracture process, as such, is very difficult. Some studies have attempted, however, to simulate fractures and created models describing the fracture process. It has been shown by several authors in the literature that the path needing minimum fracture energy is taken by crack (for example Tschegg, *et al*. 1994), and a methods of fracture energy determination are present in the works (Tan, *et al*. 1995, Tschegg, *et al*. 1995).

In many studies, the analysis of fracture surfaces is reduced to the analysis of vertical sections. Although the amount of information related to the spatial structure of the fracture is much lesser in the case of profile line analysis than when the whole fracture surface is subjected to analysis, the

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use of profiles, despite the laboriousness of their preparation (Wojnar 1990, Brandt and Prokopski 1993) makes the interpretation considerably easier and enables the application of automatic methods.

The article presents the results of examination of R_L (or R_S) concrete specimen fracture surfaces obtained in fracture toughness tests. The proposed manner has been worked out for vertical section method.

2. Relationship between the fracture surface development factor R_S and the profile roughness parameter, R_L

A measure of the degree of fracture surface development is the actual fracture surface area, *S*. Making this parameter independent of specimen dimension, it is more convenient to use the so called fracture surface area development factor, R_S. By relating the calculated value of fracture surface area, *S*, to its projection onto the reference surface, A', we obtain the value of fracture surface area development factor (Fig. 1).

The determination of the value of R_S is important inasmuch as it characterizes the real surface of a fracture, and thus, indirectly, also the actual amount of energy needed for the fracture to occur.

The parameter characterizing the profile line is the profile line development factor, R_L, introduced by Pickens and Gurland (1976). It is calculated as the ratio of the length of profile line, *L*, to its projection, L', onto the reference line (Fig. 1).

The relationship of dependence of R_S on R_L has been proposed by, among others:

- Wright and Karlsson (1981) $$R_S = 1 + \frac{\pi(R_L - 1)}{2} \approx 1.57R_L - 0.57 \qquad (1)$$
- Coster and Chermant (1983) $$R_S = \frac{2}{\pi - 2}(R_L - 1) + 1 \approx 1.75R_L - 0.75 \qquad (2)$$

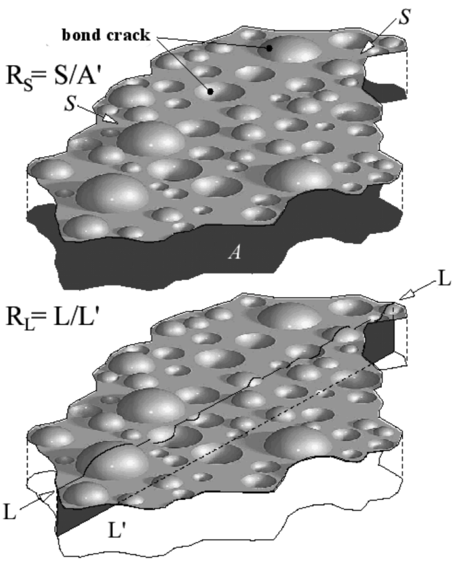

Fig. 1 The concrete fracture surface model adopted by Stroeven (2000)

- Underwood (1987) $$R_S = \frac{4}{\pi}(R_L - 1) + 1 \approx 1.27R_L - 0.27 \quad (3)$$

- Gokhale and Underwood (1989) $$R_S = 1.16R_L \quad (4)$$

The solutions given above are based on preliminary assumptions for fracture surface geometry. A universal solution that does not require any preliminary assumptions has been developed by Baddeley, Gundersen and Cruz Orive (1986). They have given a method for the determination of the surface area of any solids based on so called vertical sections not oriented in space, but only parallel to a chosen direction conventionally called a vertical direction (Fig. 2). This solution is regarded as groundbreaking in the field of quantitative fractography.

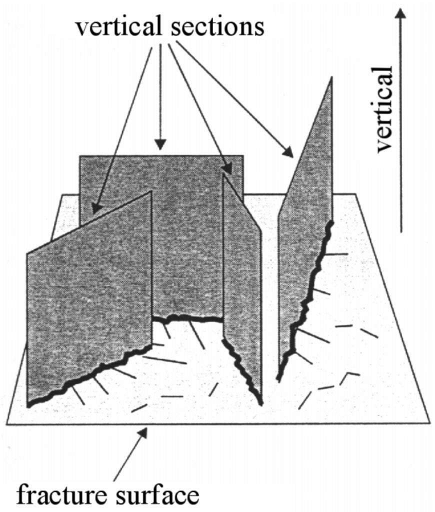

Fig. 2 Schematic diagram of the vertical section method, Baddeley, *et al*. (1986)

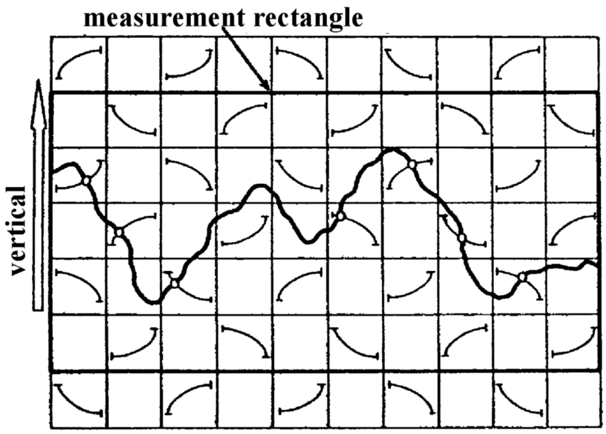

Fig. 3 Determination of fracture surface area by the vertical section and cycloid grid method

A method being some simplification of the original section method has been proposed by Wojnar (1990). In this method, the measurement of the fracture surface development factor R_S is reduced to counting points of intersection of the fracture profile with the grid of cycloids (Fig. 3), whereas the value of R_S is calculated from the formula below:

$$R_S = 2\frac{Nh}{m} \tag{5}$$

where:

N – total number of profile intersections with cycloids,

h – height of a measurement rectangle expressed as the multiple of cycloid length,

m – total number of cycloids contained in a measurement rectangle.

Gokhale and Underwood (1990) as well as Gokhale and Drury (1990) have given another, statistically accurate solution for the determination of the factor of development of an arbitrarily complex and anisotropic fracture surface, R_S. They have related the values of R_S and R_L to the following relationship:

$$R_S = \overline{R_L \Psi} \tag{6}$$

in which:

$$\Psi = \int_0^{\pi}\left[\sin\alpha + \left(\frac{\pi}{2} - \alpha\right)\cos\alpha\right] f(\alpha)\, d\alpha \tag{7}$$

where:

$\overline{R_L \Psi}$ – arithmetic mean of the products R_L and Ψ for respective vertical sections,

Ψ – function of distribution of angles along the profile,

α – angle between the normal to the profile and the vertical direction,

$f(\alpha)$ – function of probability density of angles α.

Attempts have also been made to determine the relationship $R_S = f(R_L)$ based on the experimental examination of real profiles; for example, in relation to epoxy concretes, Czarnecki, *et al.* (2001) have given the relationship $R_S = f(R_L)$:

$$R_S = 1.45R_L - 0.41 \quad \text{with } R=0.996 \tag{8}$$

The obtained results have shown that the relationship provided by Underwood (1989), which is most often used for cement concretes, may lead to underrating the value of the fracture surface development factor, R_S.

Czarnecki, *et al.* (2001) showed, at the same time, the dependence of the R_S factor on the magnification of the fracture image being analyzed, and the facts that the obtained function was contained within the domain of limiting solutions given in Wright and Karlsson (1981) and Gokhake and Underwood (1989).

A stereological analysis described in the papers by Stroeven (2000a, b), which was carried out on a model of fracture surface in concrete (Fig. 1), has proved that the R_L and R_S depend on the total amount of aggregate in the cement material, while not being dependent on the sieve curve. This conclusion is of great importance in the technology of concrete and mechanics of fracture. The problem considered by Stroeven is closely related to the transitory layer being dependent on the amount of aggregate (Prokopski and Halbiniak 2000, Prokopski and Langier 2000). By using the main stereological parameters, namely: the surface development factor, R_S, and the profile line development factor, R_L, Stroeven related them to the relative aggregate phase volume, V_V (or the relative aggregate phase area, A_A) and the relative area, S_A, characterizing the sizes of the contact layer by the following relationships:

$$\begin{aligned} R_S &= 1 + S_A - V_V = 1 + 0.5V_V \\ R_L &= 1 + 0.234V_V \end{aligned} \tag{9}$$

By combining the both equations and assuming $\pi^2 = 10$, Stroeven has obtained the relationship $R_S = f(R_L)$ in the form of:

$$R_S \approx 2R_L - 1 \tag{10}$$

Substituting Eq. (10) to the one proposed by Underwood (3), the following relationship is obtained:

$$R_S \approx 1 + 0.298V_V \tag{11}$$

while substituting Eq. (10) to that of Coster and Chermant (2) gives the relationship as follows:

$$R_S \approx 1 + 0.409V_V \tag{12}$$

With any value of R_L, Stroevens proposal yields R_S values greater than, those of Underwood, and Coster and Chermant's solutions. In the case of concretes tested Stroeven's proposal $R_S = f(V_V)$ was not confirm-the obtained correlations are not significant.

3. Experimental

Tests were carried out on concrete made of two types of aggregates: basalt aggregate and gravel aggregate. The variables in the testing plan were: water-cement ratio W/C = 0.41°¿0.61, and in the case of basalt aggregate (*B*), the amount of basalt given in relation to the sand (B/S), amounting from 1.6 to 3.0 (which gives the value of sand point, respectively, from 24.2% to 36.9%), whereas in the case of gravel aggregate (*G*), the amount of gravel given in relation to the sand *G/S*, ranging from 1.5 do 3.5 (with sand point, respectively, from 33.0% to 47.2%).

The CEM I 32,5 R Portland cement meeting the quality requirements, basalt aggregate of a fraction of 2-16 mm, unbroken gravel and 0-2 mm grain-size sand were used to the tests.

A list of the amounts of constituents in particular series is shown, respectively, in Tables 1 and 2.

Ten series of concretes differing in mixture composition were prepared, taking a constant cement/sand proportion amounting to 1:1.76 for basalt concretes and 1:1.38 for gravel concretes. For each series of concretes, four test beams of dimensions of 80×150×700 mm each with one primary crack were made for fracture toughness tests to be performed according to Mode I of fracture (Shah 1990, RILEM Report 89-FMT 1991).

Table 1 Concrete mixture basalt concrete

Series no.	Real variables		Proportions of constituents per 1 m^3 of concrete mixture				Volume of mortar V_m
	W/C	*B/S*	Cement *C*	Water *W*	Sand *S*	Basalt *B*	
[-]	[-]	[-]	[kg/1m^3]	[kg/1m^3]	[kg/1m^3]	[kg/1m^3]	[%]
1	0.44	1.81	396	174	698	1261	56.53
2	0.58	2.80	306	178	540	1508	48.00
3	0.41	2.30	358	147	631	1450	49.99
4	0.61	2.30	334	204	588	1353	53.33
5	0.51	1.60	405	206	714	1142	60.63
6	0.51	3.00	301	154	531	1592	45.09
7	0.51	2.30	345	176	609	1400	51.72
8	0.44	2.80	320	141	564	1576	45.65
9	0.58	1.81	375	218	661	1194	58.84
10	0.51	2.30	345	176	609	1400	51.72

Table 2 Concrete mixture gravel concrete

Series no.	Real variables		Proportions of constituents per 1 m^3 of concrete mixture				Volume of mortar V_m
	W/C	*G/S*	Cement *C*	Water *W*	Sand *S*	Gravel *G*	
[-]	[-]	[-]	[kg/1m^3]	[kg/1m^3]	[kg/1m^3]	[kg/1m^3]	[%]
1	0.44	1.79	451	198	623	1116	57.88
2	0.58	3.21	323	188	446	1430	46.03
3	0.41	2.50	391	160	540	1350	49.05
4	0.61	2.50	363	221	501	1252	52.75
5	0.51	1.50	469	239	646	970	63.41
6	0.51	3.50	315	161	434	1521	42.62
7	0.51	2.50	377	192	520	1299	50.97
8	0.44	3.21	339	149	467	1499	43.44
9	0.58	1.79	424	246	585	1049	60.41
10	0.51	2.50	377	192	520	1299	50.97

4. Determination of the relationship $R_S = f(R_L)$ for concrete fractures

Examinations were carried out on the fractures concrete beams, that had been previously used in fracture toughness tests performed according to Mode I (tension at bending).

The preparation of the specimens involved the making of gypsum replicas of concrete fractures, made of white gypsum, and then pouring colored gypsum on so prepared replicas. Then, the

Table 3 Results of the fractographic examinations of concrete fractures

Concrete series	Basalt concrete				Gravel concrete			
	W/C	*B/S*	R_L	R_S	*W/C*	*G/S*	R_L	R_S
1	0.44	1.81	1.2464	1.4422	0.44	1.79	1.2412	1.4217
2	0.58	2.80	1.2483	1.4413	0.58	3.21	1.2624	1.4611
3	0.41	2.30	1.2285	1.4060	0.41	2.50	1.2274	1.4013
4	0.61	2.30	1.2438	1.4256	0.61	2.50	1.2573	1.4532
5	0.51	1.60	1.2513	1.4370	0.51	1.50	1.2578	1.4486
6	0.51	3.00	1.2667	1.4740	0.51	3.50	1.2731	1.4758
7	0.51	2.30	1.2497	1.4385	0.51	2.50	1.2675	1.4659
8	0.44	2.80	1.2484	1.4387	0.44	3.21	1.2748	1.4792
9	0.58	1.81	1.2899	1.5047	0.58	1.79	1.2697	1.4653
10	0.51	2.30	1.2401	1.4248	0.51	2.50	1.2411	1.4227

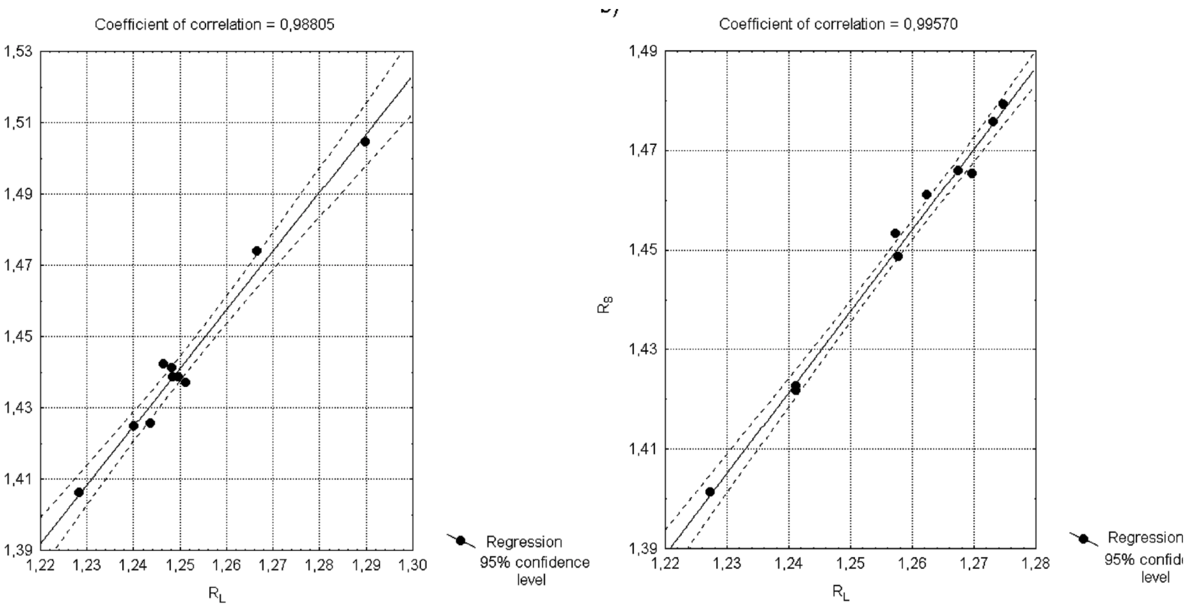

Fig. 4 Relationship of R_S=*f* (R_L): a) basalt concrete, b) gravel concrete

specimens were cut, along the longer side, into about ten 5 mm-thick slices, thus obtaining about 20 profile lines for each fracture. This choice of slicing direction was aimed at obtaining profile lines which would be approximately coincident with the direction of crack propagation.

The sliced of specimen were then scanned at a resolution of 600 dpi, while separating a 100×29 mm-long area from each of them. Computer images, in the form of bitmaps, served for obtaining information of profile lines. By using the computer program, a computerized image of profile lines was obtained. The computation of the profile line development factor R_L and fracture surface

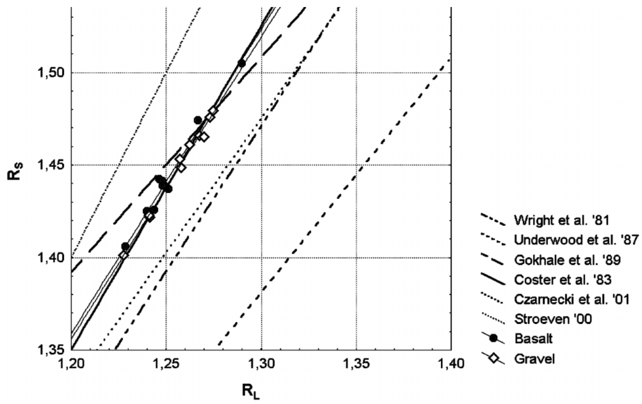

Fig. 5 Diagram of different proposals for the relationship $R_S = f(R_L)$ together with the author's own solution

development factor R_S was carried out (by using the cycloid method). By using the Grubbs test, at a significance level of 0.05, results regarded as random (gross errors) were rejected. The obtained results are summarized in Table 3.

Based on the examinations carried out, the relationship $R_S = f(R_L)$ was obtained in the form as shown in Fig. 4:

- basalt concrete R_s = 1.6431°§R_L – 0.6127, with $R = 0.988$
- gravel concrete R_s = 1.6317°§R_L – 0.6019, with $R = 0.996$

Proposals by various authors, together with the authors own solution, are shown in Fig. 5. A good agreement has been reached in the obtained values of R_L with the solution of Coster and Chermant (2).

5. Stereological tests

Flat sections of test beams used in Mode I fracture toughness tests were subjected to stereological examination.

The preparation of specimens consisted in the regrinding of concrete surfaces, followed by their washing, and, after drying, filling pores with white gypsum. Then, the concrete surfaces were reground again, and water-glass was applied on them. Thus prepared specimen for stereological examination had dimensions of 80×150 m and an area subject to analysis of 65×127 mm.

Prepared specimens were scanned at a resolution of 400 dpi. The computer analysis of obtained images was preceded by their proper preparation. In the case of the analysis of the air pore phase, the operation of eliminating accidental particles and cleaning the borders was performed on the image, whereas for the analysis of the coarse aggregate phase, the operation of pore filling and reconstruction with repeated erosion was carried out.

The results of the stereological calculations of air pores and coarse aggregate are summarized in Table 4.

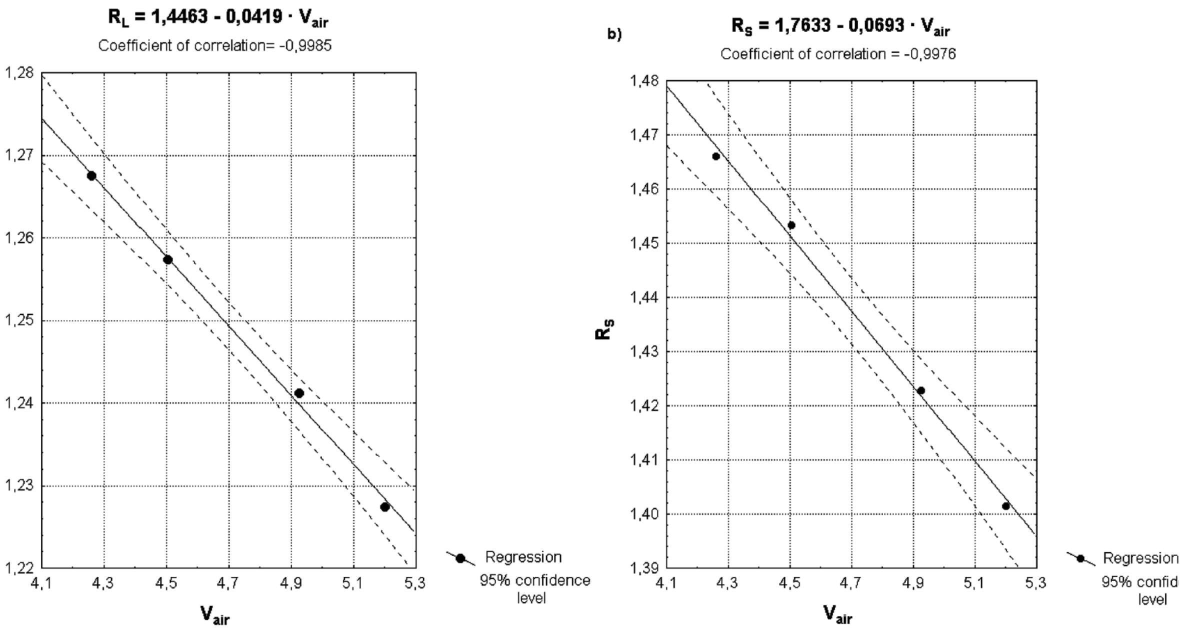

Fig. 6 Relationships of R_L and R_S vs. air pore content in gravel concrete with $G/S = 2.5$

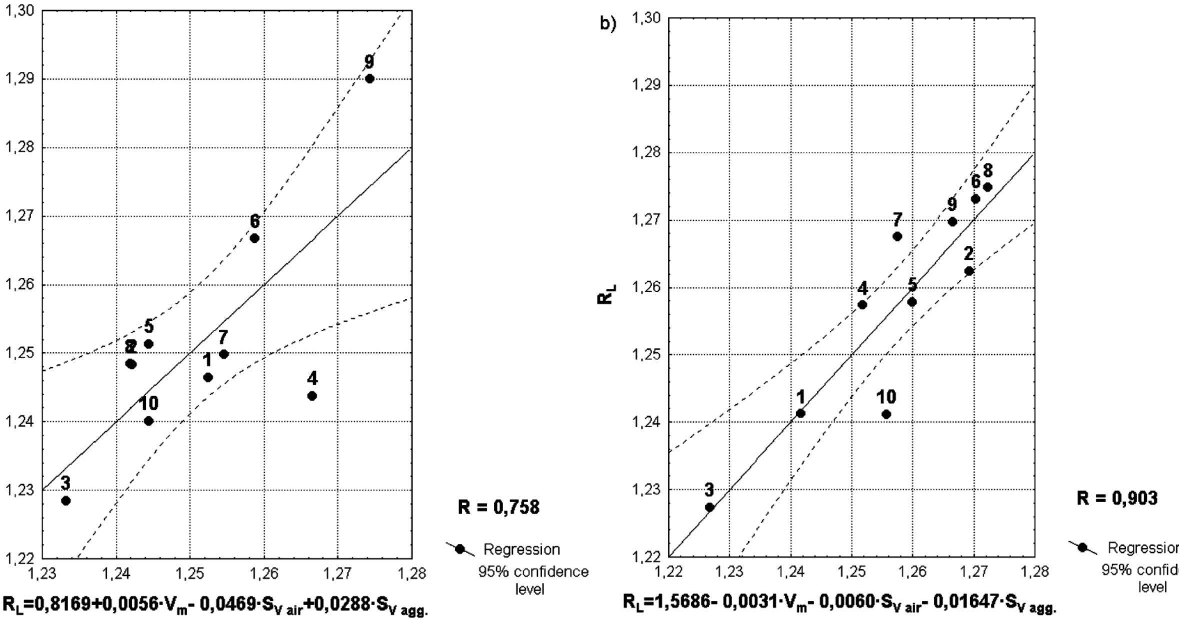

Fig. 7 Relationship between R_L, and the fraction of mortar, relative coarse aggregate area $S_{Vagg.}$ and relative air pore area $S_{V_{air}}$ in: a) basalt concrete, b) gravel concrete

Table 4 Results of the stereological analysis of air pores and coarse aggregate

Series no.	Actual values		Basalt concrete			Gravel concrete		
			Volume	Specific volume		Volume	Specific volume	
	W/C	B/S (G/S)	of air pores		of coarse aggregate	of air pores		of coarse aggregate
			V_{air}	$S_{V_{air}}$	$S_{Vagg.}$	V_{air}	$S_{V_{air}}$	$S_{Vagg.}$
[-]	[-]	[-]	[%]	[cm^2/cm^3]	[cm^2/cm^3]	[%]	[cm^2/cm^3]	[cm^2/cm^3]
1	0.44	1.81 (1.79)	3.34	1.351	6.315	4.11	2.304	8.100
2	0.58	2.80 (3.21)	2.08	0.988	7.029	4.75	2.031	8.765
3	0.41	2.30 (2.50)	3.14	1.269	6.786	5.20	2.684	10.538
4	0.61	2.30 (2.50)	1.95	0.886	6.671	4.51	1.964	8.579
5	0.51	1.60 (1.50)	2.97	1.496	5.477	4.98	2.509	5.875
6	0.51	3.00 (3.50)	1.81	0.881	7.996	6.97	2.812	9.055
7	0.51	2.30 (2.50)	1.84	0.871	6.546	4.26	2.473	8.380
8	0.44	2.80 (3.21)	1.87	0.739	7.070	6.38	2.767	8.799
9	0.58	1.81 (1.79)	1.98	0.958	5.985	3.53	1.841	6.287
10	0.51	2.30 (2.50)	2.16	0.965	6.347	4.93	2.474	8.496

6. Analysis

The analysis of results in the middle of the testing plan, with a constant value of *B/S* or *G/S*, has shown the dependence of the parameters R_L and R_S on the air porosity of the concretes tested.

The diagrams of relationships between the R_L and R_S factors and the air porosity of concrete, V_{air}, is shown in Fig. 6. For basalt concrete, the relationship of the profile line development factor, R_L, with the air porosity of concrete, V_{air}, was obtained at $R = 0.9689$, whereas the relationship of the fracture surface development, R_S, with the air porosity of concrete, V_{air}, at $R = 0.9455$. In the case of gravel concrete, the correlation coefficients were, respectively, $R = 0.9985$ and $R = 0.9976$. As the profile line development factor R_L depends on the fraction and characteristic of phases in the concrete, the effect of the fraction of mortar, V_m, relative coarse aggregate area, $S_{Vagg.}$, and relative air pore area, $S_{V_{air}}$, on the R_L was analyzed.

Obtained relationships determining the effect of the above parameters on the R_L (or R_S) have the following form:

- basalt concrete $R_L = 0.8169 + 0.0056^\circ\S V_m - 0.0469^\circ\S S_{V_{air}} + 0.0288^\circ\S S_{Vagg.}$,
  $R_S = 0.6752 + 0.0093^\circ\S V_m - 0.0695^\circ\S S_{V_{air}} + 0.0534^\circ\S S_{Vagg.}$,
- gravel concrete $R_L = 1.5686 - 0.0031^\circ\S V_m - 0.0060^\circ\S S_{V_{air}} - 0.016S^\circ\S S_{Vagg.}$,
  $R_S = 1.9673 - 0.0052^\circ\S V_m - 0.0121^\circ\S S_{V_{air}} + 0.0262^\circ\S S_{Vagg.}$

In the case of basalt concrete, the level of significance of the adopted multiple regression models was $p = 0.14$, while for gravel concrete $p = 0.013$. From the above relationships only in the case of gravel concrete the relationship is statistically significant ($p = 0.013$).

7. Conclusions

On the basis of performed investigations has been shown:

• Statistic significant correlation between R_L and R_S. With the increase in the, R_L parameter, the fracture surface development factor, R_S, also increased.

• In the case of gravel concrete statistically significant correlation between R_L (or R_S) and the fraction of mortar V_m, relative coarse aggregate area S_{Vagg}, and relative air pore area $S_{V_{air}}$.

• Obtained relationship $R_S = f(R_L)$ correspond with Coster and Chermant's solution (2), what confirm, that proposed for concretes Underwood's solution (3), reduced R_S values. Comparison however obtained relationship $R_S = f(R_L)$ with Stroeven's (10) proposal is evidently, that obtained R_S values are less that certain from Stroeven's solution.

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