ASSESSMENT METHODOLOGY OF INSTANTANEOUS ELASTIC DEFORMATION OF SEDIMENTARY ROCKS

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Abstract
A difficult problem that arises in experimental data processing is to establish the value of instantaneous elastic deformation. Based on the analysis of physical theories used in rheology, we considered that elucidating the characterisation of rheological behaviour of sedimentary rocks can be realized by taking into account the two rheological models, namely Poynting-Thomson and Burgers, through macro-analytical theories. Regardless of the theory used in the interpretation of experimental results, the requirement to assess more accurately the elastic deformation as a hidden variable occurs. For this purpose, a graphical - analytical – experimental methodology was proposed, which we consider original and which was applied in the case of sedimentary rocks from the Jiu Valley. Knowing this deformation results in the possibility of establishing the rheological parameters and the rheological coefficients included in the nuclei of creep. Such a methodology was needed because the determining of parameters α, δ, β, γ, χ would have required a whole series of integral transformations of the experimental functions that is extremely difficult.
Key words**:** *hidden variable, instantaneous elastic deformation, sedimentary rock, creep, rheological coefficients, nuclei of creep*

1. Introduction

As a result of rheological tests, especially of creep, on many types of rocks in the category of low to average strength it was concluded that if a rock is maintained for a long time under a constant load, it will fail, meaning it will break. This is due to the occurrence of the effects of viscous-plasticity, due to the creep phenomenon. The literature shows that these effects are actually given by three main mechanisms that usually occur, namely: movement of dislocations in crystals; developing a micro-cracking, especially at grain contact; mineral cement's chemical alteration of the solid particles of the rock. Rheology as a science and especially rocks creep are unfortunately still little known even now, and are still subject of numerous research studies, because all the phenomena that occur in nature - and here we refer to the case of rock massifs or earth - are carried out in time. Therefore, with these in view, there are concerns about the behavior of the rocks on the contour of the underground works, which are systems - structures that are working for a long time (whether mining works, tunnels, subways or other underground constructions). When referring to some mining workings, they can be used after the exploitation, as radioactive waste storage cavities and as a special case, a lot of attention should be given to long-term calculations of works, meaning rheological. In areas with water infiltration and where water can accumulate another phenomenon is observed, of pressure rise, leading practically to the same result. This phenomenon is known as the swelling phenomenon and occurs mainly in the presence of certain clays. If the dimensioning was not well done, the damage resulted by increasing the rocks volume can be spectacular and in the end it may even lead to breaking the apron (Toderaş, 2014).

2. Method proposed to assess the instantaneous elastic deformation

A difficult problem that arises in experimental data processing is to establish the value of instantaneous elastic deformation. The difficulty is primarily due to the greater curvature of the creep curve, in the initial stage of loading. To obtain this parameter we proposed a methodology (Toderas, 2014; 2015), which consists in the following: from the row of values obtained from the creep performance of the tests, we will consider several initial values ε(t) measured at equal intervals of time with which differences of first order, second order and so on will be calculated, based on the following relationships:

$$\begin{aligned} &\Delta_n \varepsilon = \varepsilon_{n+1} - \varepsilon_n \\ &\Delta_n^2 \varepsilon = \Delta_{n+1}\varepsilon - \Delta_n \varepsilon \\ &\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \\ &\Delta_n^k \varepsilon = \Delta_{n+1}^{k-1}\varepsilon - \Delta_n^{k-1}\varepsilon \end{aligned} \tag{1}$$

where: index n represents the number of the considered point, and k – the order of difference.

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By replacing the expressions $\Delta_n^k\varepsilon$ in $\Delta_n^{k-1}\varepsilon$, $\Delta_n^{k-1}\varepsilon$ in $\Delta_n^{k-2}\varepsilon$ and so on from the relations $\dot{\varepsilon} = \dot{\varepsilon}_0 \cdot e^{\alpha \sigma_c}$, the general equation is obtained:

$$\varepsilon_n = \varepsilon_{n+1} - \Delta_{n+1}\varepsilon + \Delta_{n+1}^2\varepsilon - \Delta_{n+1}^3\varepsilon + ... + (-1)^k \Delta_n^k\varepsilon \quad (2)$$

which will be used to establish the initial deformation $\varepsilon_o = \varepsilon(0)$ at t = 0 according to the measured values ε_1, ε_2,…..

All the terms of the relation (2) are affected by (n+1) differences, except the last term that is affected by the (n-a) difference. The calculus of the deformations differences stops at the same order, for which, in the limits of calculus, could be written that $\Delta_0^k\varepsilon \cong \text{const}$, for all the n values considered. This leads us to the idea that replacing the unknown values is allowed $\Delta_0^k\varepsilon$, for which ε_0 must be known, through $\Delta_1^k\varepsilon$ known, obtaining the relation to determine ε_o, as being:

$$\varepsilon_0 = \varepsilon_1 - \Delta_1\varepsilon + \Delta_1^2\varepsilon - \Delta_1^3\varepsilon + ... + (-1)^k \Delta_1^k\varepsilon \quad (3)$$

Let's observe, actually, that the problem of determining ε_o is reduced to the summing of the data of diagonal row that begins with ε_1 (see Table 1). Appraisement of the limit value through the deformation goes:

$$\varepsilon_\infty^c = \lim_{t\to\infty} \varepsilon(t) \quad (4)$$

rising another problem, another question: *which time must we consider*? The logical answer would be the "infinite", as in infinite time. If we were to accept the assertions of different researchers, the infinite should be considered as "time to achieve the low rate of deformation". According to the author (Toderas, 2014, 2015), as a criterion, we can consider the notion of infinitely large, which means that this "infinite" is "high time to infinity", meaning the time whose doubling will result in test conditions, to an increased deformation of up to 0.5 %, or a value of 0.005.

Table 1. *Differences of deformations to determine ε_o*

n	t	ε	Δε	Δ²ε	Δ³ε	Δ⁴ε
0	t_0	ε_0				
			$\Delta_0\varepsilon$			
1	t_1	ε_1		$\Delta_0^2\varepsilon$		
			$\Delta_1\varepsilon$		$\Delta_0^3\varepsilon$	
2	t_2	ε_2		$\Delta_1^2\varepsilon$		$\Delta_0^4\varepsilon$
			$\Delta_2\varepsilon$		$\Delta_1^3\varepsilon$	
3	t_3	ε_3		$\Delta_2^2\varepsilon$		$\Delta_1^4\varepsilon$
			$\Delta_3\varepsilon$		$\Delta_2^3\varepsilon$	
4	t_4	ε_4		$\Delta_3^2\varepsilon$		
			$\Delta_4\varepsilon$			
5	t_5	ε_5				

Such a procedure gives a superior value for ε_0, because the curve ε(t) has the convexity through ε axis, and the first derivative around zero changes convexity clearly. Knowing the value of the instantaneous elastic deformation we can proceed to establish rheological coefficients for which the calculation methodology is based on the considered creep nucleus, meaning for the rocks for which deformation under constant load tends to an horizontal asymptote, the analytical description of creep must be based on the function and so on Abel's nucleus (Rabotnov, 1966, Toderas, 2015, Todorescu, 1986) and when the rock's creep increase unlimited it is recommended the N. Rabotnov's nucleus (Rabotnov, 1966, 1969, 1980).

After marking the creep curves for each type of rock analysed based on experimental data and their analysis, we will proceed to determine the parameters and the rheological coefficients (Toderas, 2015). The original methodology for determining, proposed and presented, was imposed to be diversified in two situations, namely: in the case of using the nucleus of Rabotnov – Rozovski and respectively, for the use of Abel-type nucleus. After the analysis of creep curves, it was found that the relation between deformation and time for some rocks, is of the first rheological type and for others of the second rheological type. Therefore, to determine the rheological constants it was necessary to consider the integral equation of the hereditary theory of Voltaire type, expressed as:

$$\varepsilon(t) = \frac{1}{E_\infty}\left[\sigma(t) + \lambda\int_0^1 L(t,\tau)\,\sigma(\tau)\,d\tau\right] \quad (5)$$

in which: $\varepsilon(t)$ and $\sigma(t)$ – deformations and stresses at the time taken into consideration at the beginning of the test; $L(t, \tau)$ – creep nucleus; E_∞ - elasticity modulus in time or rheological modulus.

Therefore, for elucidating the deformation of the rock with respect to time it is necessary to determine the modulus of elasticity and the creep nucleus type of the equation (5). The type - the nature of creep nucleus can be established (Rabotnov, 1966) based on families of rock creep curves obtained experimentally in laboratory. Specialized literature (Reiner, 1958, Tan Tjong Tjong Kie et al., 1989, Tavroghin, 1974, Todorescu, 1986) states that as the creep nucleus for different behaviours and rocks functions as power, exponential, etc., can be used, recommending certain nuclei: Voltaire, Rabotnov, Vialov, Dafting - Abel, Boltzmann, Zaretki, Rjanitân, Rozovski, binomial nucleus, the nucleus with variable parameters etc. Analysing these nuclei, in the context of experimental data for sedimentary rocks tested to creep, I considered that the most accurate rendering of these values from the laboratory tests can be achieved by using the development of the equation (5) by Rabotnov (Rabotnov, 1966, 1969, 1980) as a fraction - exponential function of the form:

$$L(t-\tau) = Э_\alpha(-\beta, t-\tau) = (t-\tau)^{-\alpha}\sum_{n=0}^{\infty}\frac{(-\beta)^n (t-\tau)^{n(1-\alpha)}}{\Gamma[(n+1)(1-\alpha)]} \quad (6)$$

where: Γ is the gamma function; β, α creep parameters of the rock.

Experimental data processing based on such nucleus Ξ_α is complicated (Rabotnov, 1969). This function involves both the properties of several functions, e.g. exponential, and some customizations. For example, the rheological equation of state (5) with linear fractional nucleus type (6) for $\alpha = 0$ is transformed into an integral equation with an exponential nucleus, of the form:

$$Э_0(\beta, t-\tau) = e^{-\beta(t-\tau)} \quad (7)$$

Equations of this type are reduced to linear equations with constant coefficients and therefore the hereditary creep theory in this case can be examined by the elastic - viscous environmental theory. Deciphering the functions time operators can be achieved if for the nucleus the exponential function of fractional order is used, equation (6) and the main properties of integral operators established by N. Rabotnov and M.I. Rozovski, the customizations of this properties and also the appropriate approximations.

For the situation of non-linear deformation in time of the material system, N. Rozovski (Rabotnov, 1966, 1969, 1980) gives a more generalized situation, as:

$$\varepsilon(t) = \frac{1}{E}\left[\tau(t) + \int_0^1 K(t,\tau)\,f(\sigma)\,d\tau\right][\tau(t) + \int_0^t K(t,\tau) f(\sigma) d\tau] \quad (8)$$

where: $f(\sigma)$ is a random function of the stress state. As a creep nucleus the exponential function of fractionary order can be used belonging to N. Rozovski (Rozovski, 1958, 1960, 1961, Todorescu, 1986, Toderas, 2015), and in this case can be given:

$$\varepsilon(t) = \varepsilon_0\left[1 + a\left(1 - e^{-b\gamma t^{t-\alpha}}\right)\right] \quad (9)$$

where: $a = \dfrac{\chi}{\beta - \chi}$ and $b = \beta - \chi$; β; χ are the creep parameters (with the dimension t^{-1}) and which in case of Rabotnov, respectively Rozovski's nucleus creep, are approximated by the relations:

$$\beta = T_{rel}^{\alpha-1} \quad ; \quad \chi = \frac{E - E_\infty}{E} T_{rel}^{\alpha-1} \quad (10)$$

in which: T_{rel} is the relaxation time; E_0 momentary elasticity module; E_∞ is the rheological elasticity module; ($E_\infty < E$); α, γ are coefficients that characterize the rocks' creep and that can be experimentally determined; they do not have a constant value, no matter the type of rock, as Rabotnov notes (Rabotnov, 1966). We mention that for the case in which $\beta - \chi > 0$, the creep curve that corresponds to Rabotnov, respectively Rozovski's nucleus, is the primary creep curve and is limited by the value of deformation.

If still $\beta < \chi < 0$, without excluding the situations when $\beta < 0$, than the parameters of creep lose their sense given by the relation (10) and it will pass at Abel's nucleus, meaning an unlimited creep in which: $\varepsilon_{(t=\infty)} = \infty$ or:

$$\frac{\varepsilon(t) - \varepsilon_0}{\varepsilon_0} = a\left(1 - e^{-b\gamma t^{1-\alpha}}\right) \quad (11)$$

in which: ε_0 is the relative deformation at the beginning of load ($t = 0$), meaning the instantaneous elastic deformation (Toderas, 2015); a and b are experimental coefficients; α is a non-dimensional coefficient equal according to N. Rabotnov (Rabotnov, 1966) with 0.7 for rocks, affirmation that is still approximate and orientative, reason for which we recommend its experimental determination for each type of rock; γ is a calculated parameter:

$$\gamma = (1-\alpha)^{1-\alpha} \qquad (12)$$

that for the rocks is: γ = 0.6968453 = 0.697 according to N. Rabotnov (Rabotnov, 1966).

Resolution is to establish the coefficient a of the relation (11) and with the help of creep curves for t = ∞, value then replaced in the same expression (11) will obtain a range of values of b for different times t, from which we calculate the value of b as an arithmetic average. Rabotnov's nucleus creep, K (t - τ) depends of parameters α and β. Experimental data processing based on such a nucleus is complicated (Rabotnov, 1966) because it requires a whole series of integral transformations of the experimental functions and that the values of the parameters do not have sufficient physical clarity. As a result, we can specify the following: the norm of N. Rabotnov's functions depends of the size of β; the size of β depends of α, including the time at order -(1+α); for all rocks and other materials, sizes and α and β are negative, although analyzing data from the literature shows that in the works of Rabotnov all these parameters appear as positive, while a number of other authors parameters α and β are accompanied by a minus sign. Such a finding leads to a different understanding of the meaning of those parameters; in the expression that describes the flow curve the size is included (α +1) and a parameter α. It is desirable that in the creep nuclei to enter this size, α, determined directly by experiment. All these findings lead to the idea to propose the following form of the Rabotnov and Abel's nuclei (Ruppeneit et al., 1962), expressions in which ξ is always positive, and t_0 has the sense and value of delaying time (T_{int}). In this basis, the connection between parameters α, β, ξ, t_0 can be determined, and also, the connections between the functions of Rabotnov and the proposed one; according this, in the expression of Volter – Boltzmann that we obtained, α_∞ has a physical sense of ratio between stabilized total deformation ε_t and instantaneous elastic deformation ε_{ei}:

$$\alpha_\infty = \frac{\lambda}{-\beta} + 1 \quad \text{sau} \quad \alpha_\infty = \frac{\varepsilon_t}{\varepsilon_{ei}} \qquad (13)$$

Considering the normal deformation at creep for a constant stress σ_0 (or with a certain solicitation level Δ_i) and using the expression $\lim\limits_{t\to\infty} \int_0^t \exists_\alpha(\beta, t-\tau)\, d\tau = -\frac{1}{\beta}$, it is found that:

$$\lim \varepsilon(t) = \lim_{t\to\infty} \int_0^t K(\xi, t_0, t-\tau)\, d\tau = 1 \qquad (14)$$

This expression allows constructing standardized graphics for processing the results of creep. Graphics can be built based on tables (Rabotnov, 1966) in which the function values are given:

$$F_2(\alpha, x) = \frac{1}{t^{\alpha-1}} \int_0^\infty \exists_\alpha(-\beta, t)\, d\tau = \sum_{n=0}^\infty (-1)^n \frac{x^n}{\Gamma[(\alpha+1)(n+1)+1]} \qquad (15)$$

where: $x = x(t) = \beta\, t^{\alpha+1}$.

Using the relation between function of Rabotnov and the proposed one and also the obtained relations, it is seen that:

$$\varepsilon(t) = x(t)\, F_2\left[\alpha, x(t)\right] \qquad (16)$$

reason for which the ordinates axis will give the value of the right side of the relation (15), and the abscise axis the logarithm of corresponding time:

$$\lg \frac{t}{t_0} = \frac{1}{\alpha+1} \lg x \qquad (17)$$

Such graphics, for $0.1 \le \xi \le 0.9$, are given in Figure 1. In this representation, the unit of measurement of time on the x-axis is regarded as the size of t_0, and for the measurement of deformations on the ordinate axis is considered to be the maximum creep deformation. Analysing such a chart, it is seen the particularity of high practical importance, namely, that all curves intersect near a single point in which the normalization function of creep is 0.50 of its maximum value, size for which the value t/t_0 remains almost the same and can be considered constant, $t^* = 0.640 \cdot t_0$ for any ξ, which enables the determination of the value of t_0, independent from the value of ξ which is extremely important in experimental data.

According to this proposed methodology, the calculus stages are:

1. Rock type, mono-axial compressive strength, loading degree and creep determinations;
2. Establishing the solicitation interval t_∞;
3. Calculus of the value of deformation $\varepsilon_N(t) = \varepsilon(t) - \varepsilon(0)$;
4. Calculus of normal deformation at creep:
5. Mentioning the time t*, for which $\varepsilon^{NF}(t^*) = 0.5$;
6. Establishing the time $t_o = t^*/0.64$;
7. Calculus of logarithm $\lg(t/t_o)$ for different values of t;
8. Constructing the norm graphic of creep in coordinate system [lg (t/t_o); $\varepsilon^{NF}(t)$];
9. Overlaying the norm graphic over the standard graphic (the nomogram from Figure 1), stage that allows determining the parameter ξ;
10. Calculus of the parameters α_∞, α, β, λ.

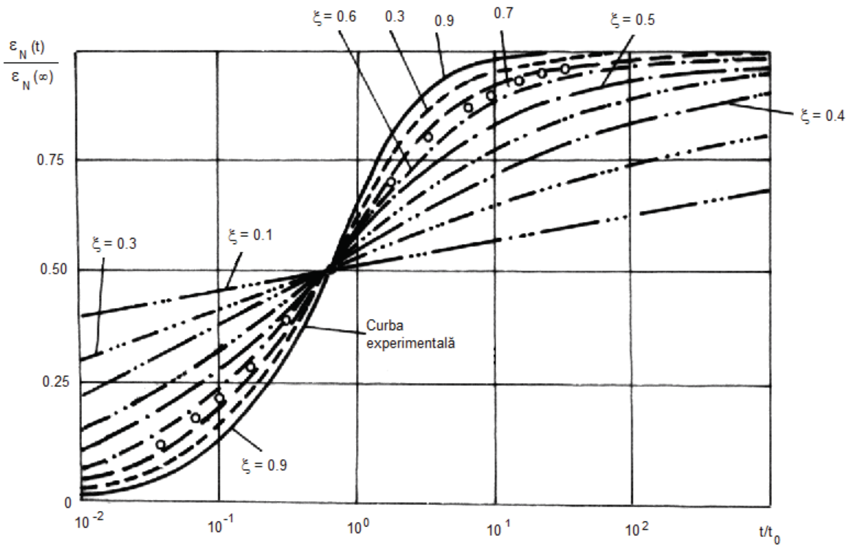

Figure 1. *Rate-setting curves of creep*

3. Results and discussions

Referring to this methodology, we mention that the time that is taken into account is the one whose doubling leads, in terms of experimentation conditions, to an increase of deformation up to 0.5 % meaning 0.005. Table 2 shows the values of the instantaneous elastic deformation obtained for the categories of analysed sedimentary rock (Toderas, 2015).

Table 2. *Instantaneous elastic deformation of sedimentary rocks studied in rheological context*

Parameters / Analysed litotypes of rocks at creep in laboratory	Mono-axial compressive breaking strength σ_{rc},[MPa]	Tests realization time, t , [hours / days]	Elastic deformation ε_e and instantaneous ε_{oi} in the field of stability, $\cdot 10^{-2}$ [%]	The value of creep deformation $\varepsilon_\infty \cdot 10^{-5}$, [%]	Ratio $\frac{\varepsilon_\infty - \varepsilon_{oi}}{\varepsilon_{oi}}$
Compact clayey sandstone unstratified gray - brown (Sample 6)	53.0	1820 75.833	1.574326 52.4834	75,319	0.4351
Compact marl unstratified slightly schistous black - brown (Sample 10)	59.6	910.08 37.92	1.543215 57.757	63,697	0.364
Compact marl (massive) gray - brown (Sample 11)	78.41	1270.08 52.92	2.0403 51.746	67,615	0.306
Clayey marl gray - greenish with fissures of $CaCO_3$ (Sample 12)	29.4	1590 66.25	2.4094 33.511	58,851	0.803
Conglomerate (Sample 17)	14.62	1085 45.208	1.60433 14.846	25,108	1.698
Arenaceous clay reddish – greenish (Sample 19)	46.0	1032 43	1.5092 38.35425	47,153	0.533
Compact marly arenaceous clay gray - greenish (Sample 28)	35.8	1124 46.83	2.2896 28.73878	45,317	0.764
Chocolate clay (Sample 29)	15.4	1479 61.625	2.3612 21.92741	29,440	1.43
Compact gray marl with fissures of $CaCO_3$ (Sample 33)	68.0	1236 51.5	1.7775 81.899	88,714	0.399
Quartz sandstone fine grained gray - greenish (Sample 37)	75.0	1092 45.5	1.6745 76.396	68,751	0.361
Compact clayey sandstone fine grained gray - greenish (Sample 38)	45.7	1116 46.5	1.51647 22.1722	33,429	0.507

Compact siliceous sandstone fine grained micaceous gray - greenish (Sample 39)	61.3	1152 48	2.9516 62.97684	53,315	0.341
Quartz carbonate sandstone (Sample 44)	72.0	1260 52.5	2.8465 65.5876	78,900	0.399
Compact gray clay (Sample 51)	24.9	706 29.416	2.41674 16.7443	32,869	0.96
Compact arenaceous marly clay slightly micaceous gray-greenish (Sample 59)	19.3	531 22.125	1.86735 43.93276	48,927	1.63
Very compact clay dark gray, (Sample 25)	32.3	5196 216.5	2.34671 66.61054	83,562	0.671
Compact clayey sandstone fine grained gray - greenish (Sample 55)	52.8	1810 75.46	1.60089 108.0042	85,382	0.423

Setting the parameters of creep nucleus was performed by own methodology. For studied rocks, the values of these parameters of creep (α, δ, β, γ, χ), changes in the range: for category of rocks with $\sigma_{rc} < 25$ MPa ($\alpha = 0.579 - 0.9136$; $\beta = 0.00055834 - 0.195243$; $\gamma = 0.695 - 0.80931$; $\delta = 0.136 - 0.6043$; $\chi = 0.0039 - 0.0903$); for category of rocks with $25 < \sigma_{rc} < 55$ MPa ($\alpha = 0.69873 - 0.893$; $\beta = 0.087666 - 0.2547$; $\gamma = 0.696 - 0.782$; $\delta = 0.12493 - 0.655718$; $\chi = 0.017052 - 0.21158$); for category of rocks with $\sigma_{rc} > 55$ MPa ($\alpha = 0.781666 - 0.896477$; $\beta = 0.0275076 - 0.44474$; $\gamma = 0.717312 - 0.79074$; $\delta = 0.457 - 1.217101$; $\chi = 0.06499 - 0.440$). Regardless of the theory used in the interpretation of experimental results, from the beginning it was necessary a proper assessment of the elastic deformation as a hidden variable (Toderas, 2015).

4. Conclusions

We proposed a graphical - analytical – experimental methodology which we consider original. The need of knowing this deformation is to facilitate as much as possible the determination of rheological parameters and the coefficients included in the creep nuclei. We looked for such a methodology because the determining of the parameters (α, δ, β, γ, χ) required a whole series of integral transformations of the experimental functions, which were extremely difficult. So that we resorted to establishing a standardization process based on rate-setting the function of Rabotnov, developing it for the nucleus of Abel and Rozovski (introducing a parameter ξ), precisely because in relation appears (α + 1) and not α. We determined the way of evaluating the normed creep deformation, on which we have built a standardized chart through which the normal function $\varepsilon^{NF}(t)$ is determined; we determined the value of the parameter t_* for which $\varepsilon^{NF}(t_*) = 0.5$ resulting the delay time T_{int} noted t_0 and finally, graphics are drawn in coordinates $\lfloor \lg(t/T_{int} = t/t_0), \varepsilon/\varepsilon_\infty \rfloor$. By overlapping these graphics resulting from experimental measurements over the standardized ones (established for $0.1 < \xi < 0.9$), we determined the appropriate value of ξ. Based on this value, we set the parameters: α, β, γ, δ and χ.

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