INFLUENCE OF STRAIN RATE ON TENSILE BEHAVIOUR OF CEMENTITIOUS COMPOSITES: INCREASING SPEED IN A STATIC TEST

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Keywords: cementitious composites, tensile testing, strain rate effect, stochastic cracking

Abstract
The present paper investigates the tensile stress-strain behaviour of a cementitious composite at different strain rates ranging from 10^{-4} s^{-1} up to 0.05 s^{-1}. The cementitious composite exists of an inorganic phosphate cement (IPC) matrix reinforced with 20 vol% of different unidirectional fibre types. The results indicate that the use of statically determined material data for dynamic or impact loading on structural components can not be recommended for these kinds of materials. Depending on the used fibre type the material is sensitive to strain rate. Effects of strain rate were found on the multiple cracking and post-cracking behaviour.

1 Introduction
Composite materials have been mainly developed in aerospace and automotive engineering. In the last few decades also civil engineers attempted to partially replace traditional building materials, such as steel and concrete, by much lighter high performance composite materials. Presently, the demands for the implementation of accidental loadings on civil constructions are increasing, since they are likely to be subject to one or more impact events throughout their lives (e.g.: vehicle crash or flying debris from an explosion). A very important issue in this field is the material behaviour that should be used for the design of structural elements. The aim of this paper is to investigate whether the statically determined material behaviour of cementitious composites can be used to design structural elements for accidental loadings. The effect of strain rate on the tensile behaviour of a specific cementitious composite is investigated by increasing the speed of a static tensile test. Subsequently, analysis of the obtained curves by means of an analytical model for the stress strain behaviour is performed.

In the available literature a lot of work can be found on the strain rate effects of polymer matrix composites containing glass or carbon fibres. In the middle nineties Barré et al. [1] discussed a large amount of literature on the strain rate dependency of polymer composite materials. In this review a wide range of strain rates was covered (from 2 x 10^{-4} s^{-1} to 2 x 10^{3}

s^{-1}) and in most of these efforts influences of strain rate on the strength and stiffness were found. However, depending on the authors there seemed to be some controversy in the results. This indicated that the results strongly depend on the components of the composite material and that there is no standard testing procedure. In more recent work of Fereshteh-Saniee, Majzoobi and Bahrami [2] tensile tests are performed on glass-epoxy composites at strain rates ranging from 0.0001 to 0.11 s^{-1}. These strain rates are comparable to the situations of a quasi static loading up to a dynamic low velocity impact event. They concluded that even at these rather low strain rates, the material was strain rate sensitive. The differences were mainly situated in the strength and in a minor way the strain rate had an effect on the stiffness. Schoßig et al. [3] did some experimental work on glass fibre reinforced Polypropylene and Polybutene-1 composites. Using a high speed tensile test, they were able to test specimens in a range of 0.007 up to 174 s^{-1}. In this study the effect of strain rate was also present in the tensile stress-strain curves. It was found that strain rates above 20 s^{-1} cause a spectacular increase in mechanical properties, while the effect at lower strain rates is present but less distinct. One of the most interesting publications on this topic related to cementitious composites was probably written by Kim, El-Tawil and Naaman [4]. Cementitious composite specimens were tested in tension at different strain rates ranging from 0.0001 to 0.1 s^{-1}. The investigated HPFRCC are steel fibre reinforced cement matrices. The fibres were mixed into the matrix in an amount of 1 or 2 vol.-%, which is rather low compared to the amounts used in this work. In these tests it was found that in some cases there is a strain rate effect on the cracking of the matrix and the strength. Although the literature reviewed here handles materials that are slightly different from the material in this work, it is clear that care should be taken if statically determined material behaviour is used for the design of structural elements that undergo dynamic or impact loadings.

2 Materials

fibre type	supplier	filament diameter [μm]	density [kg/m³]	tex [g/km]	number of filaments	E [GPa]
E-glass	Owens Corning	17	2600	600	1000	75
carbon	TOHO, Besfight	7	1800	3500	3500	170
basalt	Basaltex	14 - 17	2700	2600	2600	78
PE	DSM	12 - 21	975	176	1500	105
PVA	Nordifa	27 - 40	1300	250	200	33

Table 1. Relevant properties of used fibre types

The cementitious composites, that are most commonly developed, make use of traditional Portland cement mortars as a matrix material. The matrix material that is used in this work is called Inoganic Phosphate Cement (IPC) which exists out of a wollastonite powder that is mixed with a phosphoric acid solution containing metal ions (ratio: 80/100). The main advantage of using IPC as matrix material in comparison with Portland cement mortars is the liquidity of the cementitious matrix during production. This allows one to use production techniques typically for polymer composites, such as hand lay up and pultrusion. As a consequence much larger amounts of fibres (up to 25 vol%) can be obtained. Another advantage of IPC is its neutral environment (pH=7) after hardening. This allows one to introduce cheap E-glass fibres into the matrix material without the alkaline environment chemically attacking the fibres. However, it is also possible to introduce other fibre types into the IPC-matrix. Depending on the applied fibre type, one can obtain completely different composite behaviour as depicted in figure 1a (stiff vs. soft or strong vs. weak but deformable).

All relevant properties of the used fibre types are given in table 1. The following fibre types were selected: glass fibres because of their common use; carbon fibres for their high stiffness and strength; basalt fibres because of their good fire resistance; polyethylene (PE) fibres which are currently used in many impact applications; and finally polyvinyl alcohol (PVA) fibres for their high ductility and non linear behaviour.

3 Static behaviour of textile reinforced cementitious composites

3.1 tensile stress strain behaviour

As illustrated in figure 1b, the tensile stress-strain behaviour of a brittle matrix composite in general shows non-linear behaviour. On condition that a certain critical amount of fibres (typically about 1 vol%) is reached, the stress-strain curve contains three distinct stages. In the first stage (stage I in figure 1b) the fibres and the matrix are bonded to each other leading to linear elastic behaviour. When the composite strain reaches a value at which the maximum strain in the matrix occurs, small flaws inside the matrix will develop to form cracks. If a sufficient amount of fibres is present, the fibres will start bridging the cracks and locally take over the loads. While loading of the specimen proceeds, more cracks will develop perpendicular to the loading direction. This process is called "multiple cracking" (stage 2 in figure 1b) and is typical for brittle matrix composites. At a certain point in the stress-strain curve, the stresses in the matrix over the whole specimen are reduced making further cracking impossible. From this moment on, only the fibres will carry extra loads and the curve becomes linear again. In case this third stage is clearly present, the material behaviour is called strain hardening. The stiffness of this post-cracking stage (stage III in figure 1b) is only determined by the fibres.

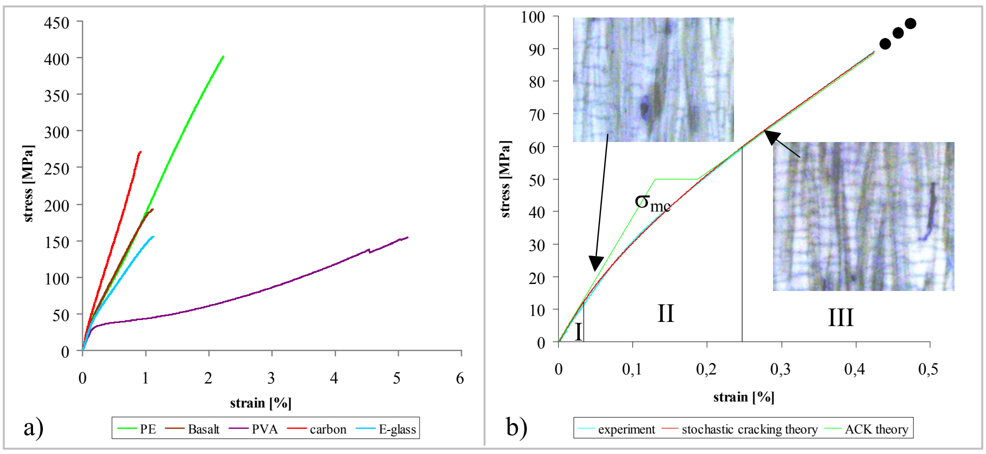

Figure 1. a) tensile behaviour of IPC specimens reinforced with different fibre types (20 vol% of fibres) b) typical stress strain behaviour of a brittle matrix composite (20% UD basalt fibres)

3.2 modeling the tensile behaviour of a cementitious composite

The specific tensile stress-strain behaviour that is described above can be modeled in several ways. A very simple model for this behaviour was worked out by Aveston, Cooper and Kelly and is called the ACK-theory [5]. In this theory, the three stages are modeled separately as illustrated by the green line in figure 1b. The composite stiffness in the first stage is modeled through the law of mixtures. Multiple cracking is assumed to occur at a deterministic composite stress value that can be calculated from the matrix strength (σ_{mu}) and which is denoted as σ_{mc}. Once a crack reaches to the fibre-matrix interface, debonding will take place due to low interfacial bond strength. The stress transfer between fibres and matrix in the vicinity of a crack is assumed to be constant. The matrix stress will therefore increase linearly with the distance from the crack. The length over which the stress transfer from the matrix to the fibres occurs is called δ and is calculated by expressing the force equilibrium along δ:

$$\delta = \frac{r \cdot V_m \cdot \sigma_m^{ff}}{2 \cdot \tau \cdot V_f} \qquad (1)$$

Within equation (1), Vf and Vm are respectively the fibre and matrix volume fraction, τ is the constant frictional shear stress and r is the fibre radius. The far field matrix stress (σ_m^{ff}) is the stress in the matrix at a point far away from the crack where there is no influence of any other cracks. This stress can thus be assumed to be equal to σ_{mu}. Within the debonding length the stresses stay below this limit and therefore no additional cracks will appear in this region. Two regimes are now distinguished: figure 2a represents the situation in which the average crack distance, defined as x, is larger than 2δ. When x becomes smaller than 2δ, the development of new cracks is no longer independent of the position of other cracks. In figure 2b the case for which all cracks have been formed is depicted. It is clear from this figure that it is not possible to introduce new cracks since stresses in the matrix are always below σ_{mu}. At the end of the multiple cracking stage the average crack distance will be equal to the final average crack distance X=1.337*δ. The average composite strain $<\varepsilon_{mc}>$ at this point can be calculated from the strain in the fibres at the end of multiple cracking. Finally, the linear third stage of the curve is modelled by the stiffness E_3 which is equal to V_f*E_f ; with E_f being the stiffness of the fibres.

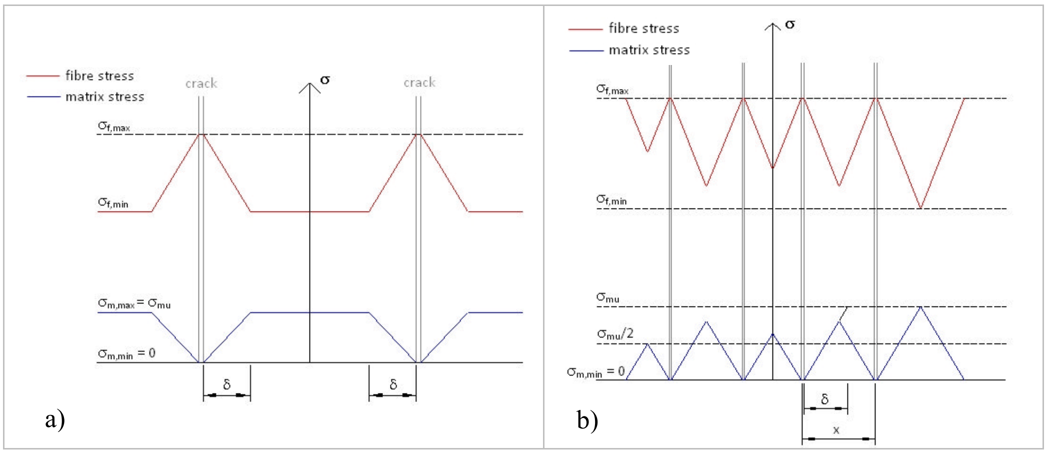

Figure 2. a) *normal stresses in fibres and matrix in case x>2δ; b) case x=X<2δ*

It is clear from figure 1b that the ACK-theory shows some disagreement with the experimental curve. The experimental curve shows that multiple cracking of the matrix does not take place at a constant stress level, but at a certain range of stresses. These observations have lead to the development of the so called stochastic cracking model [6]. The first stage as well as the third stage of the stress-strain curve is modelled completely analog to the ACK-theory. To model the multiple cracking stage, a statistical approach is applied to predict the percentage of matrix cracks that has already been formed depending on the composite stress. During multiple cracking, the mean crack distance (x) will decrease with increasing stress level and will finally become equal to X. Since the assumption of a deterministic matrix cracking value σ_{mu} is not valid in the stochastic cracking theory, a new definition should be given to the far field matrix stress, which becomes a function of the composite stress: σ_m^{ff} =

$(E_m/E_I) * \sigma_c$; with σ_c equal to the composite stress. Thus, the final average crack spacing will not be equal to the one defined in the ACK theory because of δ varying with increasing stress.

The statistical distribution function to be applied on the matrix cracking strength which is found to be most suitable to fit the experimental data is the 2-parameter Weibull distribution function [7]. This cumulative distribution function is determined empirically and can be written as in equation (2). The formula provides the necessary information on the percentage of inherent imperfections that can grow and form a crack at a certain stress level.

$$P = 1 - \exp\left[-\left(\frac{\sigma_c}{\sigma_{Rc}}\right)^m\right] \text{ and thus: } x(\sigma_c) = \frac{X}{P(\sigma_c)} \qquad (2)$$

where:	P	=	probability of fracture (cracking) at the applied stress level
	m	=	Weibull modulus; defines the width of the distribution on the matrix cracking strength
	σ_{Rc}	=	reference cracking composite stress; this is a measure for the multiple cracking composite stress

The calculation of the composite strain ε_c during the multiple cracking stage is equal to the average strains of the fibres and the matrix over the whole composite. The derivation of the formulas is described in Curtin et al. [8] and the work of Cuypers and Wastiels [6]. Two cases are observed for the calculation of the composite strain in accordance with the situations shown respectively in figure 2a and 2b. As explained previously, in the situation where $x < 2\delta$, the development of new cracks is no longer independent on the location of previously formed cracks.

$$\text{for } x >= 2\delta\text{: } \varepsilon_c = \frac{\sigma_c}{E_{cI}}\left[1 + \frac{\alpha\delta}{x}\right], \text{ with: } \alpha = \frac{E_m V_m}{E_f V_f} \qquad (3)$$

$$\text{for } x < 2\delta\text{: } \varepsilon_c = \sigma_c\left[\frac{1}{V_f E_f} - \frac{x\alpha}{4\delta E_{cI}}\right], \text{ with } E_{cI} = \text{the stiffness of stage I} \qquad (4)$$

3.3 curve fitting of stochastic cracking theory on experimental data

Substitution of equations (1) and (2) into equations (3) and (4), leads to an equation for each regime containing different parameters. Next to the obvious parameters, being the fibre volume fractions and the stiffnesses of both constituents, also the Weibull parameters m and σ_{Rc} are included in the equations. These parameters are a measure for the distribution on the matrix strength. The last parameter, $\tau X/r$, is a combination of the frictional shear stress (τ), the radius of the fibres (r) and the final average crack spacing (X). These parameters are kept in one single value to keep the curve fitting theoretical. The frictional shear stress as such can thus not be interpreted directly. Depending on the degree of impregnation the fibre radius of the model should be seen as a value in between the individual fibre radius and the radius of a fibre bundle. Also the final average crack spacing is difficult to predict and should be calibrated by experiments if interpretation of $\tau X/r$ is demanded. Nevertheless, $\tau X/r$ is a measure for the frictional shear stress and thus the interaction between fibres and matrix. Curve fitting of the described model on all experimentally obtained curves is performed to obtain objective information on the strain rate effect on the tensile behaviour of these materials. The stiffnesses in the first and the third stage of the curves are determined from the experiments and subsequently the three specific parameters (m, σ_{Rc} and $\tau X/r$) are changed within three nested loops making all possible combinations within the specified ranges and with a specified step for each parameter. The curves were fitted by using a least square method that minimizes the differences between the experimental and the theoretical curves.

4 Experimental program

The IPC matrix is reinforced with the earlier mentioned fibre types (glass, carbon, basalt, PE and PVA). The fibre bundles are impregnated by means of a self developed funnel system that is filled with matrix material. The fibre bundles are pulled through the funnel and than pressed into a mould. Specimens are cured for 24h at room temperature and post-cured in an oven at 60°C. After curing, specimens are cut at length and displacement controlled tensile tests are performed on a static test bench (INSTRON 5885H) using a mechanical grip system. Tests are performed at different displacement rates: 1 mm/min, 10 mm/min, 100 mm/min, 250 mm/min and 500 mm/min, corresponding to strain rates of 10^{-4} s^{-1} up to 0.05 s^{-1}. At each test speed, four different specimens were tested. The stifnesses in the first and third stage as well as the strength and maximum strain are evaluated experimentally as a function of strain rate. The three discussed parameters of the curve fitting are also evaluated after curve fitting.

5 Results

Average curves of the stress-strain behaviour at different strain rates for IPC specimens reinforced with different fibre types are shown in figure 3. Note that the curves are cut off at a stress level of 100 MPa or 120 MPa in case of the PVA fibre specimens. This is done because average curves are shown and not all curves have the same amount of data points. As a consequence, the strength and maximum strain values of the composites can not be derived from these average curves. For glass fibre reinforced IPC it seems that the stiffness of the third stage increases at strain rates higher than 0.025 s^{-1}. The used glass fibres might be strain rate sensitive, since the third stage is only dependent on the fibres.

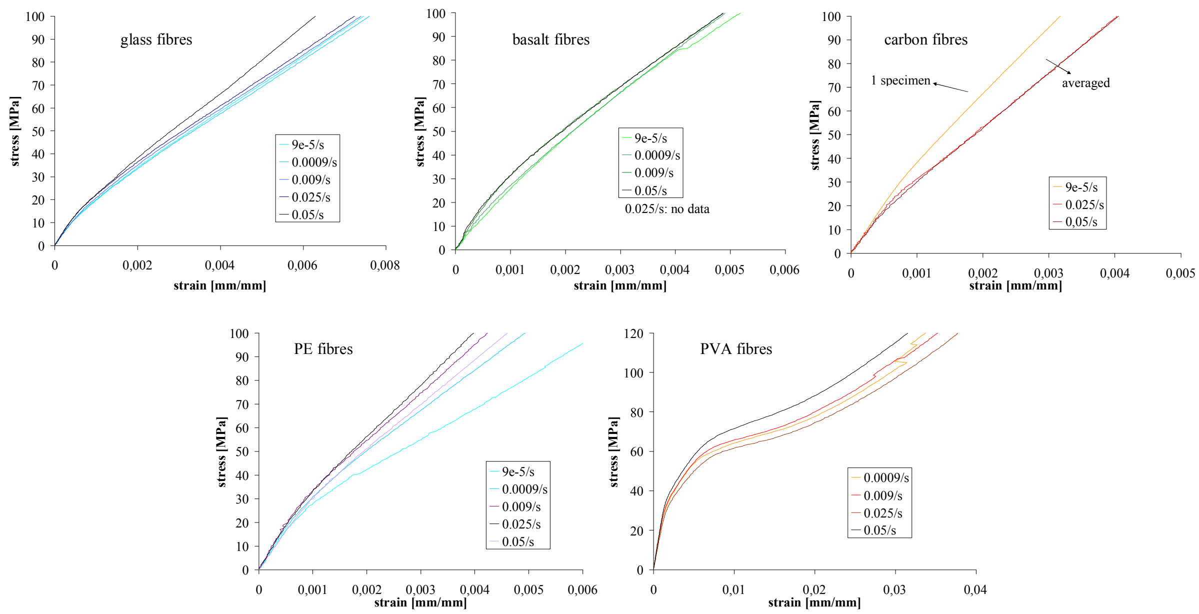

Figure 3. average stress-strain curves of specimens containing different fibre types under different strain rates

The figure also indicates that the multiple cracking is slightly delayed to higher stress levels. This is most certainly the case for the basalt fibre specimens. However, for these specimens there is no influence of the strain rate on the stiffness of the third stage. The stiffness as well as the cracking stress levels seem to decrease with increasing strain rate for carbon fibre reinforced IPC specimens. Care should however be taken with this result, because the curve at a quasi static speed of 1 mm/min (9e-5 s^{-1}) is the result of only one single test. The most obvious effect of strain rate is found for the PE fibre specimens. Clearly the stiffness of the fibres is influenced by the increasing strain rate. Concerning the PVA fibre reinforced IPC, no clear evidence of a significant strain rate effect could be found. The scatter on the results of the series of 1 mm/min was too high and thus excluded from the results.

A closer analysis of the results is performed on the data of glass fibres and PE-fibres. These series were chosen because of their most clear sensitivity to strain rate as illustrated in figure 3. For glass fibre specimens, no effect was observed concerning the strength, maximum strain and the stiffness in the first stage. The latter is illustrated in the left hand side graph in figure 4. The middle graph shows that there is an increase in the stiffness of the third stage. This increase seems to be accelerating starting from a strain rate of 0.025 s^{-1}. The parameter that is influenced most significantly by the loading speed, is the theoretical reference cracking composite stress σ_{Rc} which was obtained by curve fitting. The right hand graph in figure 4 shows a logarithmic increase in the value of σ_{Rc}. The value at a strain rate of 0.05 s-1 (18.2 MPa) has increased up to twice the initial value (9.06 MPa). The form of the trendline predicts a stagnation of the value of this parameter at loading speeds higher than the tested ones. It is possible that existing flaws inherent to the matrix before loading do not get enough time to develop to a crack at higher strain rates.

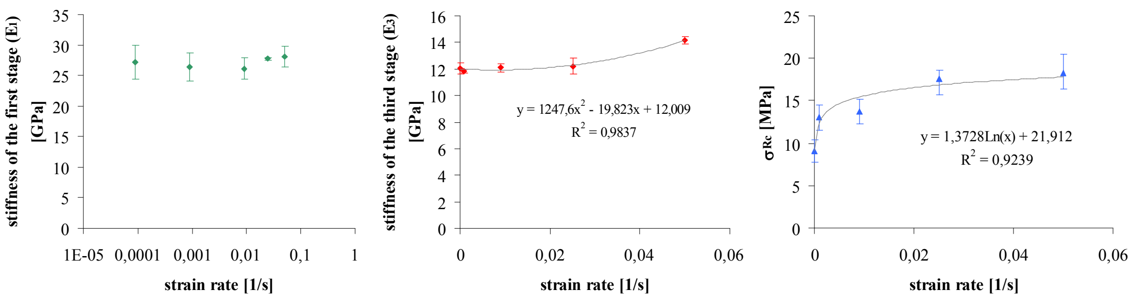

Figure 4. influence of strain rate on a) E_1, b) E_3 and c) σ_{Rc}; glass fibre specimens

Figure 5 shows similar curves for the specimens containing PE fibres. These specimens did not show an influence of the strain rate on the strength values. However, a significant increase in the stiffness of the fibres due to the strain rate is observed. Since the strength of the composite is not influenced by the loading speed, as a consequence, the maximum strain decreases due to the increase in stiffness in the third stage. This is clearly seen in the first two graphs of figure 5. From the plotted logarithmic curves one can carefully predict that the values of these properties will evolve towards a fixed value (around 2% for the strain and about 21 GPa for the stiffness of the third stage). The third graph shows the values for the Weibull parameter m, obtained through curve fitting. A linearly increasing trend is found for m. Note that the scatter becomes much higher at higher strain rates. Nevertheless, the increasing trend would imply that the Weibull distribution on the matrix strength becomes narrower. This means that the matrix cracking will occur over a smaller range of stresses.

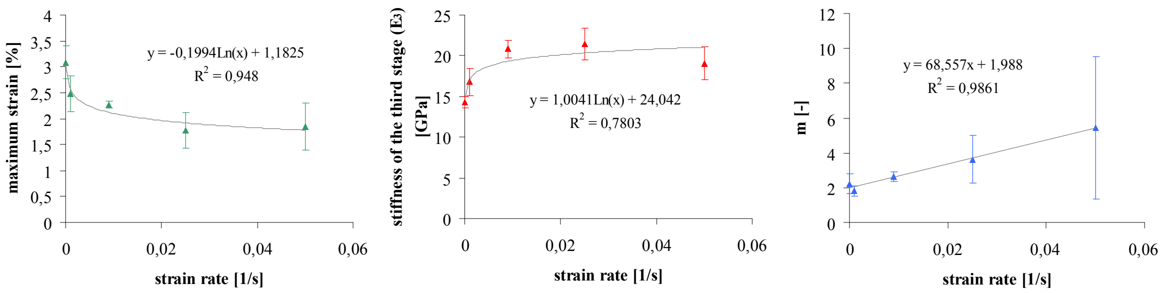

Figure 5. influence of strain rate on a) maximum strain, b) E_3 and c) m; PE fibre specimens

6 Conclusions

This paper indicates that statically obtained material data, for a cementitious composite, can not always be applied in the prediction of the structural behaviour of components under dynamic or impact loading. The influence of strain rate on this material behaviour should be investigated. For the studied IPC matrix, the strain rate influences the tensile behaviour depending on the used fibre reinforcement. For the specimens containing carbon and PVA fibres, no conclusions can be drawn due to a lack of data. Nevertheless an indication is given that PVA-fibre reinforced IPC specimens are not strain rate sensitive. Clear strain rate sensitivity was found for glass fibre reinforced IPC specimens: the multiple cracking stage is delayed to higher stress levels. Also a small influence on the stiffness in the post-cracking behaviour is noticed. The delay in multiple cracking was also found for basalt fibre specimens. In case of PE fibre reinforced specimens, the fibres do play a role in the strain rate sensitivity of the composite. The stiffness in the third stage is significantly increased and as a consequence the maximum strain decreases with 30%. Although strain rates under impact loads are higher than the tested ones in this work, valuable data on this topic is provided.

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