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DYNAMIC CHARACTERIZATION OF ADOBE IN COMPRESSION: THE INFLUENCE OF FIBRE FRACTION IN SOIL MIXTURES

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Abstract. Adobe is one of the most ancient forms of masonry. Adobe bricks are sundried mixtures of clay, silt, sand and natural fibres locally available joined together using mud mortar. Adobe structures are largely spread in areas of the world prone to earthquakes or involved in military conflicts. Unfortunately, almost no literature concerns the dynamic assessment of soil-based masonry components. From earlier research, it was derived that the mechanical behaviour of adobe in statics fits in the class of quasi brittle materials. Its resemblance with cementitious materials concerns the main failure modes and the constitutive models in compression. This study deals with the experimental characterization of adobe components response in dynamics. It is aimed to study and quantify the rate sensitivity of adobe material from bricks at a wide range of strain rates, from statics up to impact conditions. In particular, the influence of fiber reinforcement in the mixture on the mechanical behaviour of the material has been addressed. Adobe bricks are commonly mixed using organic content locally available in the field, from straw to chopped wood. Fibres are added to prevent shrinkage cracks during the air drying process. In modern materials such as concrete, inclusion of artificial fibres is originally meant to enhance the mechanical performance of the material, benefiting from the selective properties of reinforcement and binder. An experimental campaign was carried out in a collaboration between Delft University of Technology, Dutch Ministry of Defence, TNO and the Joint Research Centre (JRC) of the European Commission. Two types of bricks were tested. They both had the same soil composition in terms of mineralogical family and soil elements proportions but only one was mixed using straw and wood. Cylindrical samples were subjected to compression tests at different rates of loadings in compression: low ($\dot{\epsilon}_1$ = 3 10^{-4} s^{-1}), intermediate ($\dot{\epsilon}_2$ = 3 s^{-1}) and high ($\dot{\epsilon}_3$ = 120 s^{-1}). High strain rate tests were performed using the split Hopkinson bar of the Elsa-HopLab (JRC). For each test, high resolution videos registered the failure process and force-displacement plots were recorded. Elaboration of results revealed clear trends in the dynamic material behaviour. Adobe, as concrete, is sensitive to the loading rate. The rate effects on the main properties of the material in strength and deformation are also analytically and numerically quantified. Rate sensitivity and failure mode are significantly influenced by the inclusion of fibers in the mixture. These effects are quantified, interpreted and compared with modern SFRC. This paper presents the experimental campaign and the obtained results. Moreover, physical interpretations for the observed trends are discussed. Finally, new formulations for the assessment of the dynamic increase factor of the compressive strength of adobe are proposed.

1 INTRODUCTION

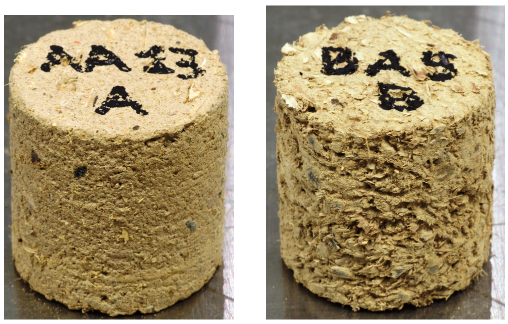
Recent progression of asymmetric conflicts in urban environments in Europe urges the development of new approaches of material design for strategic and sensitive structures of the city [1]. Among the most recent proposals, cement matrices are reinforced using fibers of steel (SFRC). The mechanical properties in tension of steel adhering to the matrix increase the strength and the toughness of the material [2]. As a result, SFRC is effective on resisting high loading rate impacts with lower penetration depth or residual velocity values in case of ballistic conflicts [3]. Actually, mixing matrices with fibers is not a new practice but starts with the use of adobe in the history of construction materials, a masonry of raw earthen bricks and mud mortar [4]. Raw mixtures of soil have been mixed using randomly distributed fibers locally available in the field since ancient Egypt and earlier [5]. However, the reason for this inclusion in Adobe is mainly due to the need of preserving structural integrity and to prevent initial damage during shrinkage inherent air drying processes under sun of cast mixtures [4]. Instead, the effects of such inclusion on the mechanical performance of soil mixtures have been scarcely addressed in literature. This knowledge becomes necessary because Adobe structures are spread in areas of the world prone to earthquakes or currently involved into military operations, with spread examples of structural failures and human losses every year [6]. In this global conjuncture, the comprehension of the dynamic mechanical properties of Adobe, including the assessment of the role of fibers, is of paramount importance for safety and protection tasks for international organizations. To this end, an experimental campaign has been performed in collaboration with Delft University of Technology (TU Delft), TNO, Dutch Defence Academy, Dutch Ministry of Defence and the Joint Research Centre of the European Commission. It was aimed at assessing the contribution of natural fibers on the dynamic properties of Adobe bricks in compression. Two typologies of masonry bricks were tested: they had the same soil composition but only one was mixed using natural fibers. Samples have been subjected to static tests and impact tests at strain rates $\dot{\epsilon}_2 = 3\ s^{-1}$ and $\dot{\epsilon}_3 = 120\ s^{-1}$. Strain rates of the order of hundred could be achieved using the modified Hopkinson bar at the HopLab of the Joint Research Centre. Elaboration of results gives the static and dynamic properties of Adobe at a wide range of applied strain rates and it revealed qualitatively as well as quantitatively the role of fibers in the mechanical response. The experimental campaign, its elaboration and interpretation are presented in this study. Information derived provides insights also for research on modern composite materials such as high performing steel fiber reinforced concrete (SFRC). In fact inclusion of fibers in cement mixtures is still not a standardized procedure and randomness on the properties according to geometry of fibers and interactions with matrices after inclusion is sometimes observed in literature [7]. Furthermore, concrete reinforced using natural fibers have been tested in recent years to reduce environmental impact inherent current building industry [8].

2 THE EXPERIMENTAL CAMPAIGN

The experimental campaign has been jointly performed at laboratories of TU Delft, Netherlands defence academy and of the Joint Research Centre.

2.1 Materials

Two types of Adobe bricks were selected for testing. Their soil constitution was the same but only one of them contained large amount of natural fibres. Cylindrical samples of 40mm in diameter with unitary slenderness were drilled from both types and surfaces rectified to achieve base plane parallelism with a tolerance of 0.1mm (Figure 1).



(a) (b)

Figure 1: Example of tested fiber free (a) and reinforced (b) Adobe samples

2.2 Standards and Setup

Granulometric composition was determined on three samples per type. Density and moisture content at laboratory condition were determined on fifteen samples per type according to NT Build 333. Uniaxial compression tests at an approximate strain rate of 3 10^{-4} s^{-1} ($\dot{\epsilon_1}$) and dynamic tests at an approximate strain rate of 3 s^{-1} ($\dot{\epsilon_2}$) were performed on five samples per type. Displacement controlled analyses were performed prescribing a constant velocity of respectively 1mm/min and 90 mm/sec to the steel platens of a hydraulic machine. Strain rates of the order of 120 s^{-1} ($\dot{\epsilon_3}$) were obtained using a modified Hopkinson bar with 40mm diameter input and output bars made of aluminium. The input pulse was generated through the pre-stressing of a portion of the input bar and abruptly releasing it. A scheme of the machine provided with geometrical information is graphically reported in Figure 2. The incident stress pulse generated a deformation velocity of about 4200 mm/s for the applied test conditions. From each test at all loading rates, stress-strain plots and photo images of failure during analyses were derived. Average stress-strain plots were derived normalizing each curve over the corresponding cross section areas and heights. Despite common practice, it should be noted that this is rigorous only when deformations in the post peak part of the curve are not too localized

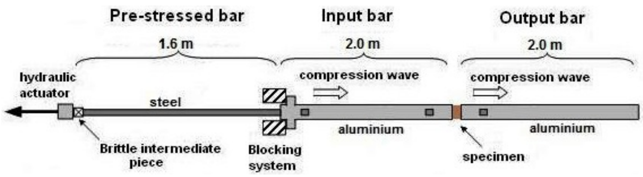


Figure 2: Schematic picture of the JRC modified Hopkinson setup for compression tests at $\dot{\epsilon_3}$

2.3 Results

Soil composition for both types consisted in 24-25% of clay, 47-48% of silt and 27-28% of sand. Type B was mixed with 18% b.w. of organic content constituted by a variety in shape and size of wooden or straw fibers max 20 mm long.

Density of the resulting bricks was higher for Type A ($\approx$ 1800 kg/m^3) than for Type B ($\approx$ 1100 kg/m^3) while moisture content after drying was similar for Type A ($\approx$ 2.2%) and Type B ($\approx$ 2.4%).

Failure of cylinders of Adobe in statics was characterized by a mixed vertical-diagonal cracking pattern (Figure 3). Cracks started from random points of the sample spreading over the surfaces. Samples from Type B were characterized by more diffuse and less visible systems of cracks which started at later deformation stages than for Type A. Cracks often followed the visible fibre orientations and samples remained coherent until large displacements (Figure 3a). As a result, deformation parameters as the critical strain at peak load ϵ_c and ductility d at 20% of decay of strength in softening were larger for Type B (mean±standard deviation value for ϵ_c = 5.7±0.6 % and d = 12.1±0.2 %) than Type A (ϵ_c = 2.4±0.3 % and d = 3.7±0.2 %). Instead values for strength and elastic modulus were higher for Type A (f_b = 2.6±0.2 MPa and E = 170±30 MPa) than Type B (f_b = 1.4±0.2 MPa and E = 54±7 MPa) as in Figure 3a. Failure modes and shapes of stress strain curves were similar for both types at the two loading rates of the dynamic regime (Figure 3(b-c)). However, the first cracks had a more straight orientation than in statics, particularly for fiber free samples, while a more randomly diffused crack pattern remained associated to Type B even at early stages of deformation. Also the stress-strain plots remained characterized by the same regions observed in statics: a linear elastic phase proceeded and followed non linearity and softening after peak load. Tests on Type A samples at $\dot{\epsilon_3}$ were sometimes connoted by a plateau at peak load. For both dynamic strain rates, it was observed that the addition of fibers in the mixture had the same effect on failure modes and material properties as observed in statics with respect to fiber free Adobe (Figure 3b for $\dot{\epsilon_2}$ and Figure 3c for $\dot{\epsilon_3}$). Dynamic increase factors (ratio between the dynamic and static values of a mechanical property) for the compressive strength of the tested adobe are of the order of 2 at $\dot{\epsilon_3}$. For each rate, compressive strength increased more for Type A (f_{b_2} = 3.5±0.1 MPa and f_{b_3} = 4.8±0.1 MPa) than for Type B (f_{b_2} = 1.6±0.2 MPa and f_{b_3} = 2.3±0.2 MPa) (Figure 4). Higher uncertainty concerns the assessment of the influence of rate on the deformation material properties. Critical strains and ductility were less affected by loading rates in dynamics and a maximum dynamic increase factor of 0.75 was registered considering all tests. The tendency of the parameter was to slowly decrease with rate. This trend was more clear for Type B (ϵ_{c_2} = 5.2±0.5 % and ϵ_{c_3} = 4.5±0.4 %) than Type A (ϵ_{c_2} = 2.5±0.4 % and ϵ_{c_3} = 1.8±0.2 %)(Figure 4).

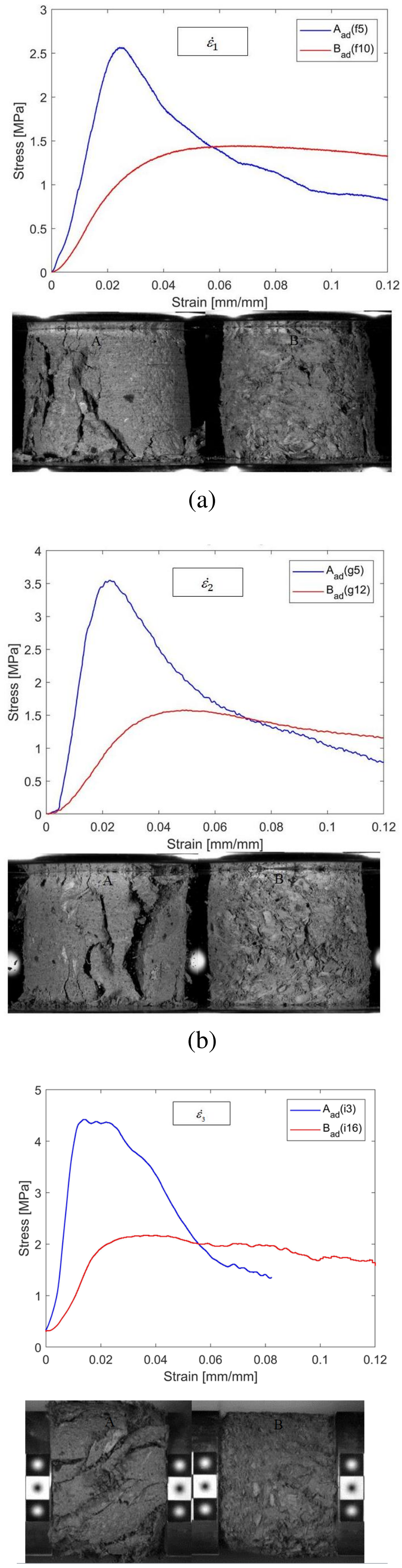


Figure 3: Examples of σ-ϵ plots and cracking pattern images at 0.12% for Type A (left) and Type B (right) in statics (a) and dynamics at $\dot{\epsilon_2}$ (b) and $\dot{\epsilon_3}$ (c)

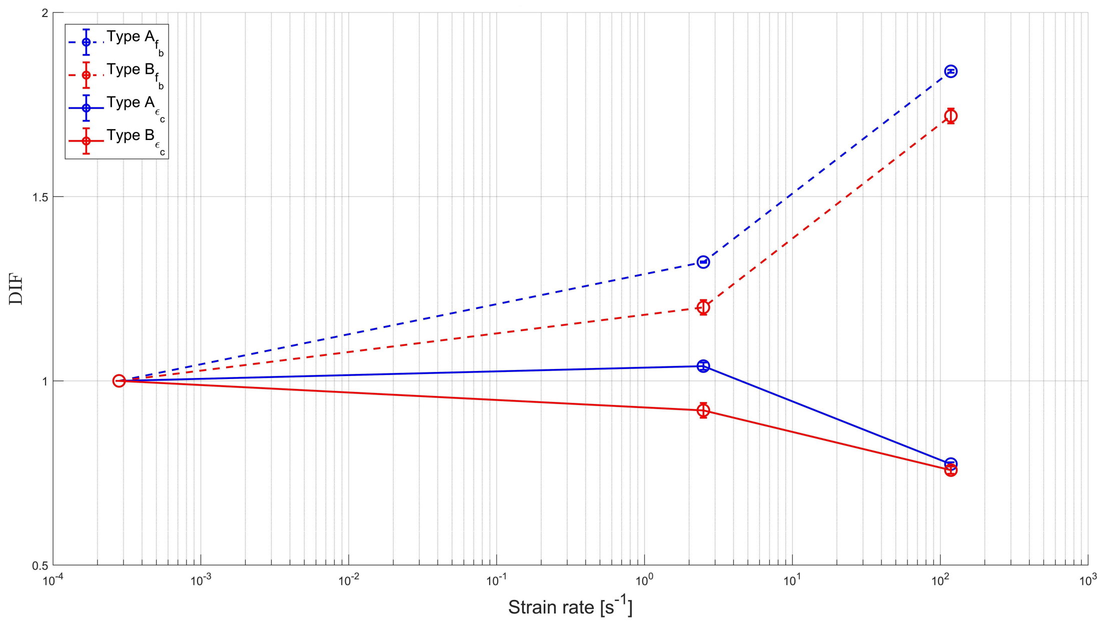


Figure 4: Average values and standard deviations of the dynamic increase factors for compressive strength and critical strain as a function of rate for Type A and Type B

3 ANALYSIS OF DATA IN STRENGTH

As for cement-based materials, the mechanical parameters of the tested Adobe showed sensitivity to the applied rate of loading. In concrete compression strength can increase up to three times in dynamics [9] and guidelines suggest to consider an increment of 85% in the design for impact loadings for ordinary concrete subjected to high strain rates [10]. For the tested Adobe material, rate sensitivity in strength is slightly less pronounced than reported for concrete. In Figure 5 dynamic increase factors for adobe lie on the inferior boundary of the cloud of data usually associated for concrete [9]. This is especially valid at strain rate $\dot{\epsilon_3}$. This is in agreement with the only other source of information available in literature regarding adobe tested at high strain rates (Figure 5) [11].

The rate of enhancement of the strength in compression can be quantitatively addressed in dynamics using rate dependent functions. They are usually implemented into numerical models to simulate cementitious materials subjected to highly dynamic loadings [12, 15].

The most widely used reference to design the compressive strength of normal concrete ($f_b \leq$ 50 MPa) in dynamics is the CEB-FIB model [14]. It defines DIF for strength in compression as :

$$\begin{cases} D.I.F. = (\frac{\dot{\epsilon}}{\dot{\epsilon}_s})^{(1.026\alpha)} for\ \dot{\epsilon} \leq 30s^{-1} \\ D.I.F. = \gamma(\frac{\dot{\epsilon}}{\dot{\epsilon}_s})^{(0.33)} for\ \dot{\epsilon} \geq 30s^{-1} \end{cases} \quad (1)$$

where $\dot{\epsilon}$ is the current strain rate in dynamics, $\dot{\epsilon}_s$ is the reference static strain rate ($3\ 10^{-5} s^{-1}$), $\alpha = \frac{1}{5+9(\frac{f_b}{f_{bo}})}$, $\gamma = 10^{6.156\alpha - 2}$ with f_b a reference strength value of 10 MPa. Figure 5 shows the CEB model for a concrete of 30 MPa of strength. It well matches with experimental data on concrete but clearly overestimates rate dependency for Adobe. Overestimation is even enhanced if the values of the reference parameters in eq.1 (f_b and $\dot{\epsilon}_s$) are adapted to the tests performed on Adobe. This is shown in the second plot of Figure 5, where the f_b of the CEB is equal to 1.35 MPa, taken as the average of the compressive strength of 110 static tests collected from literature for traditional adobe in [4]. Little literature is concerned with the study and evaluation of the dynamic increase factors for steel fiber reinforced concretes [16, 17]. Strength is showed to increase proportionally less than for plain concrete, similarly to what observed for the tested Adobe in Chapter 2. In [17], the CEB model was modified prolonging the yielding strain rate ($\dot{\epsilon}_s$=53 s^{-1}) and to decreasing the dynamic increase factor beyond with approximately a factor 0.7. The corresponding DIF function for a 80 MPa concrete reinforced using steel fibers is also plotted in Figure 5. The modified CEB model for fiber reinforced concrete now underestimates experimental response of adobe but is closer to the data associated to samples mixed with straw. Besides CEB standard, logarithmic functions of order *n* and corresponding parameters *A* of the type $D.I.F. = A_o{+}A_1 log(\frac{\dot{\epsilon}}{\dot{\epsilon}_s}){+}(...)A_n log(\frac{\dot{\epsilon}}{\dot{\epsilon}_s})^n$ are usually used in literature to address DIF for concrete by interpolation with experimental data [10]- [13]. A polynomial function of third order was used to interpolate average values of strength of both types at high strain rates. Best fit parameters were determined using the least square method : They correspond to A_0 = *0.7;* A_1 = *0.03;* A_2 = *0.03* for Type A and A_0 = *0.6;* A_1 = *0.02;* A_2 = *0.03* for Type B. The shape well interpolates experimental data and the best fit curve for Type A is shown in Figure 5. Besides the quantitative assessment of compressive strength, the depiction of the softening slope of response is of paramount importance in case of non linear seismic analyses [20]. These rate dependent formulations can be applied to extend constitutive models developed in statics to the dynamic regime. This is the approach used in [21] for concrete masonry, where analytical $\sigma - \epsilon$ curves developed for the static assessment in compression ($\dot{\epsilon}$=3 10^{-6} s^{-1}) were adapted via a multiplying factor of 1.25 on both deformation and strength parameters of the model to fit the experimental response at $\dot{\epsilon}$=0.01 s^{-1}. A similar approach has been attempted in this study. A constitutive model for the static assessment of concrete [25] is used for Adobe and modified as in eq. 2 to account also for the response in the dynamic regime:

$$\sigma = (kE_o)(\frac{n}{n-1+(\frac{\epsilon k E_o}{DIF f_b})^n})\epsilon \qquad (2)$$

where E_o is the ratio between the compressive strength and the corresponding strain and *n* a parameter that in the original work of [25] varies between 2-4 for mortars and 1.5-5 for concrete depending on porosity and internal matrix composition. In addition to the original model, *DIF* in eq.2 corresponds to the logarithmic function previously calibrated for Type A and Type B and *k* is a dependent function derived interpolating the experimental curves from tests on Adobe in dynamics. *n* was calibrated for each test on Adobe in statics. Mean best fit values are found to be almost double for Type A (3.1 $\pm$0.2) than for Type B (1.7 $\pm$0.1), both characterized by low levels of scatter. The model fits well all experimental curves of response of Adobe in statics also in softening regime, independently from fiber inclusion in the mixture (Figure 6(a-b)). This confirms the findings by authors that numerical models currently used for concrete like materials are suitable to address the response of adobe [22, 23]. Furthermore, statistical inference on *n* for the two types of tested adobe suggests that this is a property of the soil mixtures, quantitatively linked to the 18% of fibers added. A *n* value of about 3 and 2, respectively for Type A and Type B, was kept as a material constant for the constitutive assessment of adobe in dynamics. In the dynamic regime, an expression for *k* was derived interpolating all the experimental curves from tests on Adobe for the two strain rates. Multivariate analyses lead to a best fit formulation for $\frac{k}{DIF} = (3e^{-3}(n-1))(1+0.03w)\dot{\epsilon} + ((1.2{-}0.1n)(1{-}5e^{-3}w))$. Statistical inferences confirm higher rate dependence for higher water content levels (*w*) and minor organic content (*n*). Figure 6(c-d) shows the analytical-experimental comparisons between the constitutive model calibrated in statics and integrated with the rate dependent functions and the mean experimental curves associated to each type for both strain rates. Considering the wide range of strain rate targeted and the natural scatter inherent tests, the model reproduces the dynamic experimental plots well.

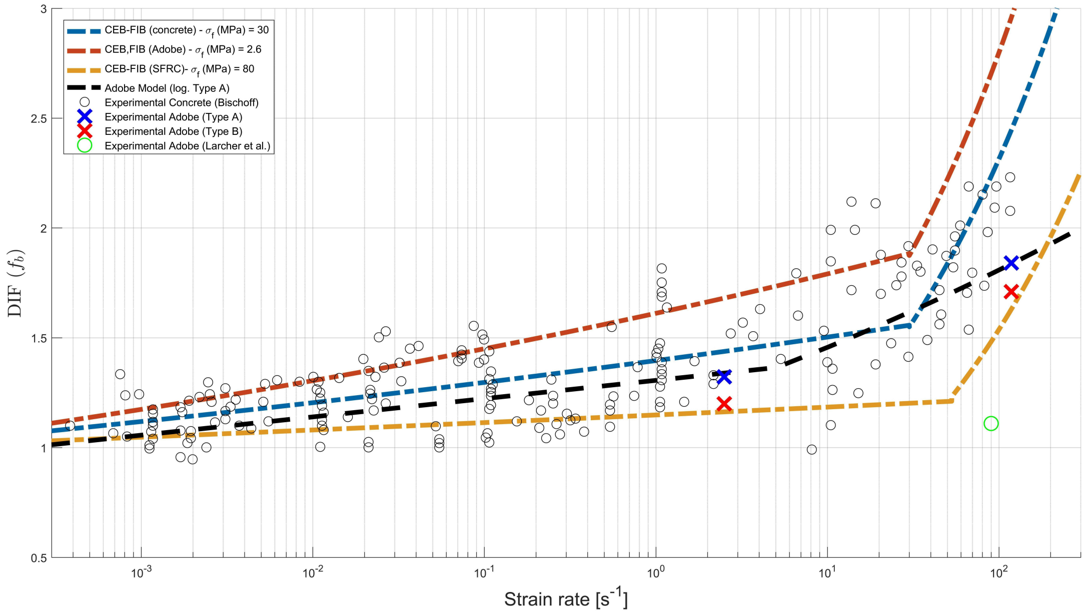
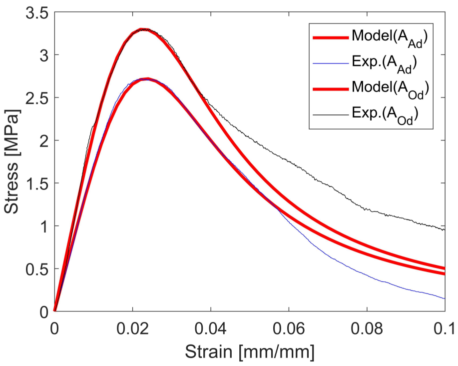
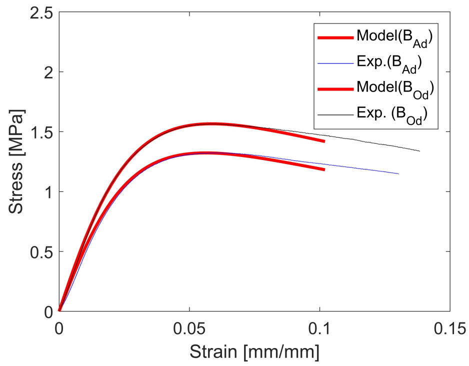


Figure 5: various DIF models with respect to experimental data on concrete [9] and Adobe



(a)



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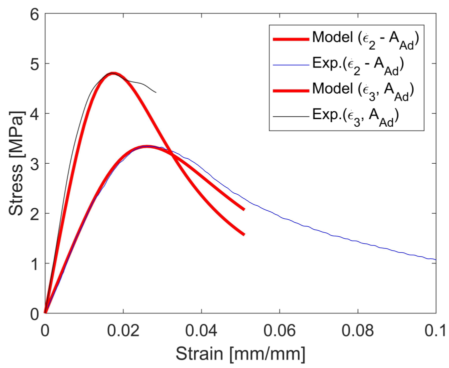

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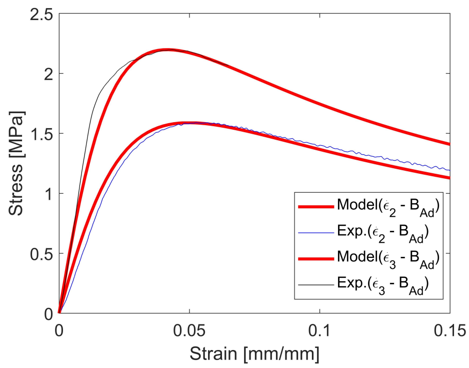

(d)

Figure 6: Experimental-analytical comparison in statics for air dried and oven dried Type A (a) and Type B (b) and experimental analytical comparison for air dried Type A (c) and Type B (d) in dynamics at the strain rates $\dot{\epsilon_2}$ and $\dot{\epsilon_3}$

4 PHYSICAL INTERPRETATION OF RESULTS

This last chapter is aimed at physically interpreting the observed trend that relates fiber inclusion in soil mixtures to a decay of the mechanical properties in strength: in statics in terms of compressive strength and in dynamics in terms of DIF. Actually, as shown in Sec. 3, also the few multi-strain rate experimental tests available in literature on fiber reinforced concrete reveal lower DIF compared to plain concrete. This was also explained for concrete as a result of a higher homogeneity level provided by steel fibers at a meso-scale [16, 17]. This is consistent with the positive effects of fibers on the toughness and strength of the material in statics [17]. In fact, fibers in concrete have been lately added to enhance the mechanical performance of the material through the employment of the specific mechanical properties of both elements and including their effective adhesion. Furthermore, fiber addition in modern materials is usually limited to 6% b.w. Instead, mixing soil with considerable amounts of natural fibers represents an ancient practice for Adobe, originally meant to reduce shrinkage cracks inherent air drying processes of bricks mixtures during production processes.

The lower sensitivity of strength to high strain rates exhibited by Adobe samples containing fibers is interpreted by linking principles of fracture mechanics to hypotheses on the specific heterogeneity level of fiber enriched mixtures of adobe. For a generic quasi brittle material tested in dynamics, the enhancement of strength performance can be explained considering a change of fracture planes at a meso-scale with respect to statics [26]. In statics, given a limited set of flaws inside the material, the most critically sized and oriented ones undergo crack initiation and propagation. As these microcracks approach the vicinity of other propagating ones, they may interact and coalesce into a macro crack which leads to loss of structural integrity and failure at a macro-scale [27]. In fact, if propagating flaws encounter stiffer areas, they have the time to deviate around them bridging into macro-cracks and the fracture and stress path with minimum energy demand is defined. Instead in dynamics, loadings characterized by short time duration and high supply rates force simultaneous cracks at multiple spots also through the stiffer areas of the material [28]. As a result, more diffuse systems of short and straight cracks initiated at multiple weak spots are often observed in quasi brittle materials such as concrete, corresponding to higher values for compressive strength and strain at peak [9, 26]. Also in Adobe a strength enhancement is displayed at high strain rates, which is lower than the typical ranges associated to concrete. Crack patterns in dynamics of the tested Adobe clearly show parallel crack orientations to the loading direction mainly at the first stages of deformation in dynamics. This is especially the case for fiber enriched mixtures, which experience the lowest rate of increment in the performance and whose failure pattern in dynamics tends to follow the static ones with negligible influence of rate on deformation capacity. The theory of fracture mechanics hooks up the experimental evidence for adobe given that the rate of enhancement of the dynamic material properties depends on the spatial distributions of the micro-flaws inside the material, that is by the level of uniformity of a mixture. If the number of micro-flaws increases, the probability of interaction increases also in case of dynamic loadings [29]. It means that if density of initial flaws distribution is sufficiently high, the effect of loading rate on the crack bridging processes will be limited and a stress path with a energy demand close to statics can be defined also in the dynamic regime (Figure 7). This can explain the lower DIF of Adobe with respect to concrete and the lower DIF of fiber enriched mixtures with respect to fiber free ones. But this interpretation is also consistent with the depicted trends experimentally derived in Sec. 2 of lower strength values associated to bricks mixed with fibers in statics. This is actually a common trend in literature and only in rare cases inclusion of fibers determine higher mechanical performance in adobe [4]. This can be explained assuming that fibers constitute weak interfaces of the meso-structure and their inclusions in soil mixtures potentially determine extensive areas of de-adherence between the adopted soil matrix and natural organic materials, which enhance porosity in the mixture and exasperates the material heterogeneity [24]. This is especially the case for mixtures containing high amounts of organic content. The absence of standard and guidelines for Adobe, including production chains and controls allow randomness in the determination of homogeneity requirements at a meso-scale, which is exasperated by aleatory of locally available raw resources and vernacular building practices. The success of fiber inclusion on the performance in strength is indeed determined by the bonding between the different micro-elements which determines the meso structure of the mixture; that is by soil mineralogical family, elements proportions and organic materials, sizes and shapes [22]. To a minor extent, this also counts for modern building materials. Void distribution and porosity weaken the strength also in mortar used in modern masonry [31] and also in steel reinforced concrete, the rate of enhancement on the mechanical performance depends on the percentage of steel reinforcement [17]. The major contribution associated to the presence of fibres both in case of soiled and cement binders is related to its role on the material ductility [17]. Its role is visible from early stages of deformation up to the softening phase of the material response and it is due to the stress-transfer in the matrix. Fibers allow stress to be transferred across cracks, constraining the crack width and holding together the vital cores of the soil particles and restricting lateral deformation.

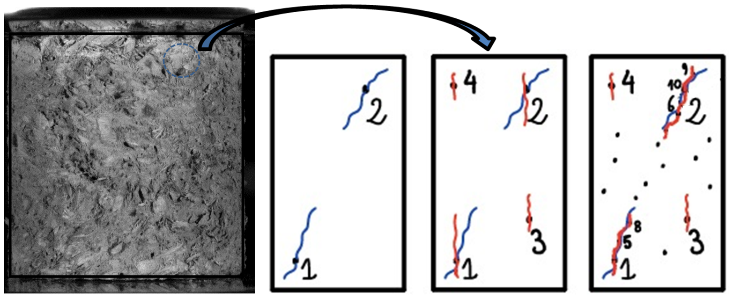

Figure 7: Schematic meso-scale representation of micro-flaws numbered in descending order of entity and crack paths, in blue lines for statics (left) and in red in dynamics for low (center) and high (right) number and density of flow distribution

5 CONCLUSIONS

An experimental campaign was performed on specimens of Adobe, a masonry made of unsaturated soil bricks and mud mortar. Two types of bricks were tested. They had the same mineralogical composition but they differed in the amount of fibers. Samples were subjected to compressive loadings at three different strain rates corresponding to static, intermediate and high rate loading conditions. Tests revealed that the material properties of Adobe in strength are enhanced by the rate of loading while a minor influence is encountered in the deformation performance. Strength increased more in mixtures not containing fibers. This was interpreted as the result of an exasperated porosity which weakens inter-particles bonds between fibers and matrix. The effect of fiber inclusion on the strength of a material and on its rate of enhancement in dynamics is indeed determined by the bonding established by the different components of the mixture. Their interactions determine the homogeneity of its meso-structure. For a given set of soil mineralogical family and elements proportions, optimization studies can determine the proportions, geometrical and physical properties of the fibers which allow the best material performance, configuring its effect as a fully reinforcing role.

Data from the experimental study have been also quantitatively elaborated to address a constitutive model for Adobe in compression valid for both static and dynamic regime which also includes calibrated rate dependent functions to quantify the experimental dynamic increase factor in strength of Adobe.

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