Influence of the fiber reinforcement on the dynamic behavior of UHPC

Author(s) & Affiliation:

Oliver Millon, Anne Kleemann, Alexander Stolz

Fraunhofer Institute for High-Speed Dynamics, Freiburg, Germany

Abstract:

The paper at hand reports about an extensive experimental study with the focus on the optimization of a fiber reinforced UHPC and the later investigation of the dynamic behavior of high resilient structural members. These members consist of a layered structure made of performance optimized UHPC and a core made of normal strength reinforced concrete and were developed for the application in wall elements and columns. Both functions should be addressed under consideration of material costs: load bearing and protective function. In this scope one focus of the study was led on the optimization of a standard UHPC with respect to its mechanical properties under both quasi-static and dynamic loadings. This UHPC is used as protective layer to resist extraordinary and extreme loadings e.g. coming from impact and detonations. There, the fiber reinforcement is known to be the crucial component, which essentially controls the mechanical properties. In this sense the study investigated different mixtures of UHPC under variation of the fiber content, the fiber geometry and the fiber material. Finally, the best mechanical properties were found for a mixture using a fiber cocktail consisting of steel and PVA fibers. This combination leads to an improvement of the mechanical properties in comparisons to standard UHPC mixtures and of the resistance against high temperatures. With dynamic fracture energy of about 18700 N/m a significant increase of about 50 % was realized in comparison to a standard UHPC with similar fiber content.

Keywords:

Extreme loading situations, Stress waves, Fiber reinforcement, Blast test, Split Hopkinson bar, Dynamic characterization

1. Introduction

The building constructions of the future tend to be higher, slender and more flexible in use. The built infrastructure is faced with a change in loading, as well. Reasons are the tendency of increasing ground cost with the consequence that in the design phase construction room will be saved and the building height will increase. Furthermore, higher loadings and the occurrence of extreme loading scenarios are expected to influence the building design and the material choice essentially. In the past an increase of extreme events was observed, mainly being the result of intended and accidental man-made hazards. Since it is not foreseeable, that the cultural and economic differences will be solved, an increasing tendency in the frequency of occurrence and in the intensity of loading is expected. The most hazardous events result from detonative events (blast loading) or impacts of solid bodies with high velocities. Additionally, for the future an increase of extreme natural events due to strong winds and wind related loads resulting in impacts of solid bodies is expected. To guarantee highest protection for the society, measures have to be developed increasing the resistance, which leads to an increase of the resilience of building constructions – the field of material science comes into play.

Ultra-high performance concrete is a material with strongly improved mechanical properties with respect to brittleness, energy absorption capacity and strength. With its increased performance [Millon, 2015; Nöldgen 2009], not only a large step in the direction of realizing slender and higher construction is done, but also a material is investigated, which offers better protection in case of extreme events [Millon, et al. 2012]. Especially the addition of high strength fibers leads to an enormous increase of the performance in terms of the energy absorption capacity. However, due to the specific material components, the material cost increases with improved properties. Solutions are required combining both protection and cost-effectiveness.

In this scope the paper at hand shows a solution on how to combine normal strength concrete and UHPC used as a protective layer to design resilient structural members fulfilling both: the protection in case of an extreme loading event and an exactable increase of the material cost. Considering both requirements, a sandwich construction applicable for the essential load carrying building elements, like walls, columns and slabs is developed, which is pre-fabricated and offers an improved protection in case of detonative loading under acceptable costs. The article primarily reports about the material design of the protective layer made of UHPC by the means of variation of the fiber reinforcement with respect to fiber material, degree and geometry of the fiber reinforcement.

2. Extreme loadings and dynamic material characterization

Extreme loading situations differ strongly from the loadings considered in the quasi-static building design. Such loadings show an inconstant force profile over the loading time. Furthermore, the loading time is significantly lower than under quasi-static loading situations within the range of microseconds to milliseconds. Often, such loadings are characterized by stress-waves into the attacked structure. The intensity of the dynamic loading is expressed by the strain rate, defining the change of the strain due to loading, divided by the time of occurrence. Finally, the strain rate is a classification parameter which is not only used to define a dynamic load, but also to show the dependence of mechanical properties of materials. Especially brittle materials show a marked effect of the strain rate on their mechanical properties.

Typical extreme loading events causing high strain rates in the loaded structures are detonations of gases, high explosives or impacts of solid bodies caused by natural and man-made events. Especially for detonative scenarios the mass of the explosive item and the stand-off to the building component control the failure modes. Detonations with a large stand-off result in a global structural response – bending failure is observed. In case of close-in or contact detonations, local damage, like punching, is caused. Essential structural damage is caused in terms of a destruction of the microstructure of the loaded material, leading to higher criticality to the stability of the single building component and the whole building construction. The same behavior is observed under impact. From this perspective it is important to analyze the behavior of materials and building structures under loading scenarios causing different failure modes to get an overall understanding of the material behavior under various loading situations.

The loading of a structure under close-in detonation is schematically documented in Figure 1. The damage due to such an event is characterized by two failure zones, the compression and the tensile failure zone.

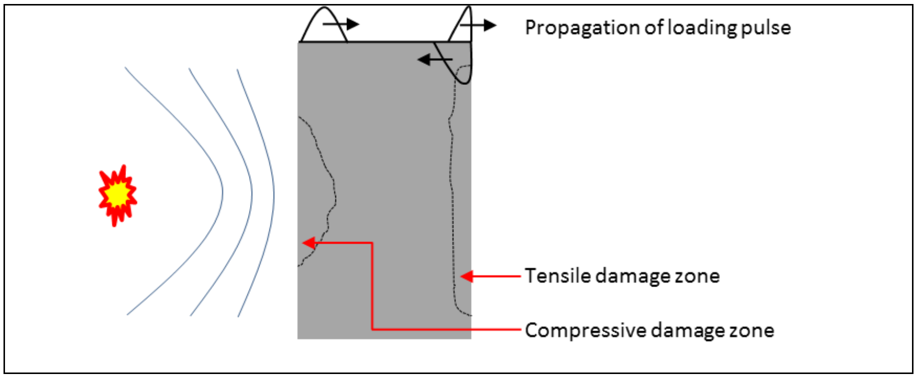

Figure 1. Stress wave propagation and resulting damage of a concrete structure

The compression failure zone, located at the attack face of the element, shows a crater of a certain diameter and depth. Due to the high acting loading pressures the concrete microstructure were destroyed and the fragments were blown out. Due to the blast loading stress waves are induced into the structure. The stress waves propagate through the material. With progressive propagation the stress wave amplitude is damped, because of the energy consumption of the material resulting in internal cracking. At the rear face a large cracking on the surface and a spall plane is established. Since tensile stresses occur on the rear face and brittle materials show a large higher compressive strength than the tensile strength, the dimension of the damage on the rear face is much larger than the one on the attack face. The spall plane occurred due to stress transmission and stress wave propagation in the material. If the intensity of the loading is high enough, a break-through occurs by superposition of both zones. Figure 2 documents exemplarily the damage of a concrete plate due to an impact loading. The above described failure zones can be clearly identified.

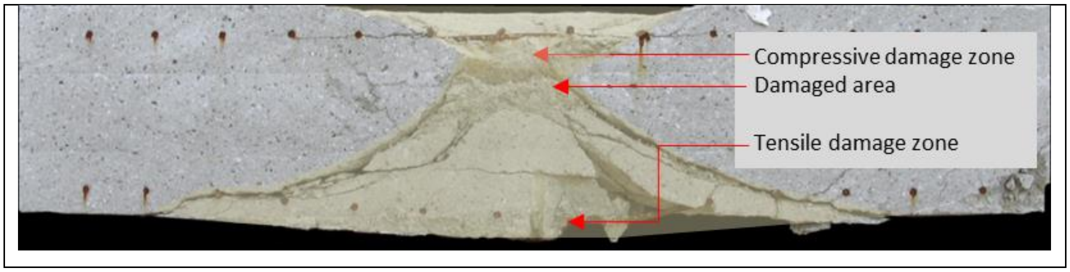

Figure 2. Local damage of a concrete structure due to impact or close-in detonation

Several studies of the past report about an effect of the strain rate on the mechanical properties [Malvar 2008]. Especially brittle materials are very sensitive to tensile loadings resulting in a significant increase of the tensile strength compared to the compressive strength. This behavior results in a higher resistance to dynamic loadings. The sources for this observation are still in scientific discussion, however, the crack initiation and its development propagation and the loading velocity play an important role. In the past some formulations were developed showing the increase of the compressive strength and the tensile strength of concrete under uniaxial loadings. Millon [Millon 2015] used the formulation of Malvar and Crawford [Malvar 2008] and adopted, based on experimental investigations on several strain rates, these mathematical descriptions developed for normal strength concrete for a specific fiber reinforced UHPC, shown in Figure 3.

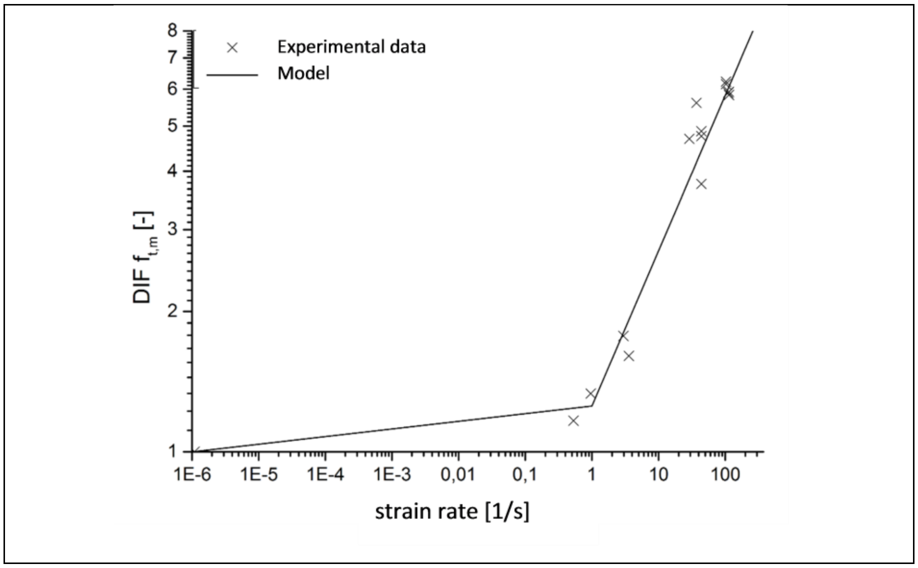

Figure 3. Strain rate effects for the tensile strength of normal strength concrete, according to formulations of Malvar and Crawford [Malvar 2008] adopted to UHPC by [Millon 2015]

Since standardized test procedures for the characterization of brittle materials are not available, the derivation of dynamic material properties follows scientific, acknowledged methods. The split-Hopkinson Bar technology is such a method, applied worldwide for various materials in diverse configurations to get a large range of dynamic mechanical properties.

The tensile behavior of brittle materials is of special interest, because, as described above, the dimension of the tensile damage is significantly larger compared to the compressive damage. This results from the higher sensitivity of such materials to tensile loadings. Consequently, the tensile strength is significantly lower than the compressive strength.

Thus, the optimization of the material performance under dynamic loadings is mainly driven by the improvement of the tensile properties. The accomplishment of split-Hopkinson Bar experiments in the tensile or the spallation configuration lead to essential dynamic tensile properties within a strain rate range of 10 to 200 s^{-1}. From spall experiments the tensile strength, the Young’s modulus and the fracture energy can be derived. The related spallation configuration consists of a loading facility, a cylindrical incident bar and a data acquisition system, which is capable to capture the measurement signals with the required high sample rate. In such an experiment the test sample is fixed on the free end of the incident bar (Figure 4) [Millon 2015, Mechtcherine et al. 2011].

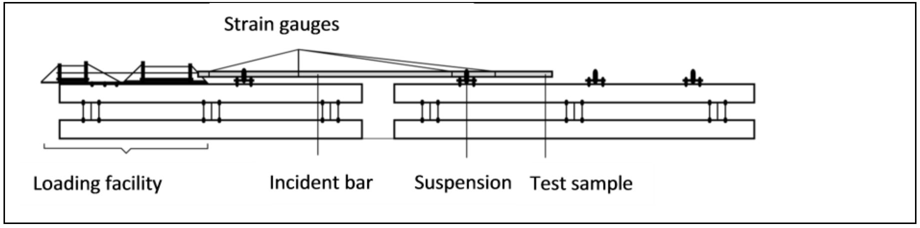

Figure 4. Experimental setup of the split-Hopkinson Bar in the spallation configuration

The loading is generated by a striker, propelled by a specific accelerator to bring the impactor to the required impact velocity. Due to the impact of the striker on the attack face of the incident bar, a loading pulse is generated consisting of a compressive wave and a de-compressive wave. The shape of the stress pulse is controlled by the impact velocity (stress amplitude) and the length of the striker. The stress pulse propagates axially towards the specimen with the longitudinal sound speed of the bar material (C_L). On the surface bar-specimen, a portion of the pulse is transmitted by the specimen, the rest reflects because of the different impedances of the involved materials. The transmitted pulse propagates through the specimen, reflects on its free end into an inverse pulse, which travels back towards the bar. By reason of superimposition of both pulses, tensile stresses occur in the specimen leading to fragmentation (spalling (Figure 5)), if the dynamic tensile strength is exceeded.

The evaluation of spall experiments bases on the momentum conservation and the energy conservation, the linear wave theory in elastic materials and the free surface approximation for the particle velocity [Schuler 2004, Millon 2015, Brara & Klepacko 2002, Mechtcherine et al. 2011]. The derivation of the fracture energy is accomplished by the consideration of the momentum transfer during the spallation process. All mathematical formulations used for the determination of the dynamic properties are given below.

$$E_{dyn} = \rho \cdot C_L^2 \tag{1}$$

$$f_{t,dyn} = \frac{1}{2} \cdot \rho \cdot C_L \cdot \Delta u_{pb} \tag{2}$$

$$G'_{f,dyn} = m_2 \cdot \Delta v_2 \cdot \dot{\delta} \tag{3}$$

ρ denotes the material density, C_L the longitudinal wave speed, Δu_{pb} the pull-back velocity, m_2, Δv_2 the mass and the change of the velocity of fragment 2, and $\dot{\delta}$ the crack-opening velocity, respectively. The longitudinal sound speed is derived from different strain measurements on defined positions of the sample. The pull-back velocity is calculated from the particle velocity signal captured at the specimen's free end. For further detailed information we refer to [Schuler 2004, Millon 2015, Mechtcherine et al. 2011].

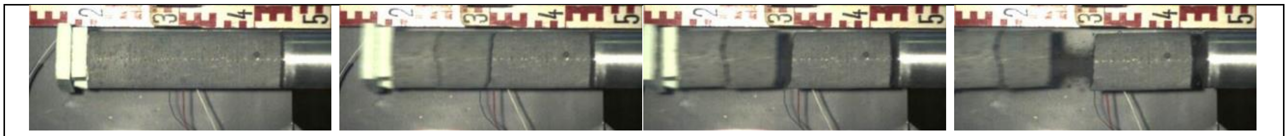

Figure 5. Spallation process in a Hopkinson-Bar experiment on a sample made of UHPC B4Q

3. Optimization of the mechanical properties of UHPC

3.1. Definition of the UHPC

Ultra-high performance concrete is a material which shows strongly improved mechanical properties which bases on three principles:

- Reducing the water-binder ratio,
- Using high strength aggregates,
- Using large amount of fine and finest aggregates,

The application of these principles leads to a dense and porous reduced microstructure with a good bond behavior between aggregates and matrix, and fibers and matrix. Since in the project a material improvement should be realized with respect to increasing the dynamic performance under mechanical loading, however also under high temperature loading, a starting point of the mixture has to be chosen. The research on UHPC is in progress worldwide, resulting in different mixtures for fine and coarse aggregate UHPC. Within this study the UHPC mixture B4Q [Fehling et al. 2004] with a steel fiber content of 1 percent by volume was chosen as a starting point, since this material was already characterized well. B4Q is a coarse aggregate UHPC using basalt as high strength coarse aggregate, quartz sand and fine quartz as fillers. A high performance Portland cement with low alkali content and high resistance against sulfite was used as the primary binder. Micro-steel fibers are added to reduce the brittle behavior. Additionally, the steel fibers have a positive influence on the strength, the softening behavior and the energy absorption capacity. The basic material composition of B4Q consists of high strength Portland cement, coarse aggregate (basalt) and fine aggregate (quartz), fine quartz, silica fume, and superplasticizer. The water-binder ratio is around 0.19.

Table 1 documents the essential quasi-static (qs) and dynamic (dyn) mechanical properties of the B4Q in comparison to a normal strength concrete. The fundamental differences in the performance with respect to strength and fracture energy are visible. In the characterization the quasi-static tests have been accomplished with a strain rate of about 10^{-6} s^{-1} for both materials, while the dynamic tests have been carried out in a range between 50 s^{-1} and 150 s^{-1}. However, due to the dense micro-structure, the behavior of B4Q under high temperature loading is poor.

Table 1. Comparison of the essential quasi-static and dynamic material properties of normal strength concrete (C30/37) and UHPC B4Q

Property	**Unit**	**C 30/37**	**UHPC B4Q**
Compressive strength (qs)	MPa	30	170
Tensile strength (qs)	MPa	2.9	7.0
Young’s modulus (qs)	MPa	31900	52900
Fracture energy (qs)	N/m	130	10300
Tensile strength (dyn)	MPa	15.5	42.4
Young’s modulus (dyn)	MPa	32000	52300
Fracture energy (dyn)	N/m	590	10000

3.2. Study on the material optimization

The investigations of Millon [Millon 2015] show an improved performance of the B4Q in comparison to normal strength concrete with respect to the damage and finally to the residual strength. However, especially under detonative loading a lack of energy absorption capacity was found, the damage was too high and consequently, the residual strength was too low. Further material development was formulated to increase the protection capability of UHPC. The results were supported by dynamic tests on building components [Millon et al. 2012]. Microscopy and computer-tomography analyses show a destruction of the bond between fibers and matrix without fiber rupture. Consequently, the strong improvement of the fracture energy, meaning the energy absorption capacity of the material, is controlled by the steel-fiber reinforcement. Though, in consideration of the residual loading capacity the improvements are not sufficient to resist extreme loads without significant damage. Especially, if the material is used as a protective layer surrounding a normal-strength concrete core, a higher increase of the performance with respect to higher energy absorption capacity is required. In this sense, material research following the goal of increasing the performance of the standard UHPC mixture was accomplished. Since the mechanical properties of UHPC are controlled mainly by the fiber reinforcement and the interaction between fibers and surrounding concrete, a variation of the fiber reinforcement was focused on in the study. Table 2 documents the variation parameters of the fiber reinforcement. Beside the fiber geometry and the fiber content, the fiber material was varied in order to improve the performance under high temperature loading, as well. Finally, a fiber cocktail consisting of both, steel and synthetic fibers was investigated.

Table 2. Definition of the fiber reinforcement with respect to the mixture

	Fiber material	**Fiber length [mm]**	**Fiber diameter [mm]**	**Fiber degree [Vol.-%]**
Mixture B4Q	Steel	9	0.15	1.0
Mixture 1	Steel	6	0.2	1.5
Mixture 2	Steel	12	0.2	1.5
Mixture 3	Steel	17	0.2	2.0
Mixture 4	PVA	12	0.1	1.0
Mixture 5	Steel + PVA	12.0 / 12.0	0.2 / 0.1	1.0 / 1.0

Since the polyvinyl alcohol (PVA) fibers show a high tensile strength and a lower melting point than steel fibers, this kind of fiber material was intended to use to increase the mechanical properties as well as to increase the resistance of UHPC in case of high temperature loading.

3.3. Results of the experimental study

The accomplishment of spall experiments on the Hopkinson bar leads to the dynamic tensile properties within a strain rate range of about 150 s^{-1}. For the classification of the mixture with respect to the compressive strength and derivation of strain rate effects, the properties under quasi-static loadings are established, as well. All results are summarized in Table 3.

Table 3. Results of the quasi-static (qs) and dynamic (dy) characterization

	Compressive strength [MPa]	**Tensile strength (qs) [MPa]**	**Young's Modulus (qs) [MPa]**	**Fracture Energy (qs) [N/m]**	**Tensile strength (dy) [MPa]**	**Young's Modulus (dy) [MPa]**	**Fracture Energy (dy) [N/m]**
Mixture B4Q	173.0 ()	7.0 (0.5)	52900 (1900)	9300	42.4 (3.2)	52300 (2700)	10000 (1900)
Mixture 1	162.1 (4.1)	9.3 (1.1)	56200 (400)	3400	48.3 (4.2)	58300 (600)	9970 (840)
Mixture 2	147.2 (1.5)	12.0 (1.1)	53400 (700)	7700	45.7 (1.3)	60400 (400)	12700 (960)
Mixture 3	162.4 (1.8)	15.7 (1.6)	56300 (1000)	13200	37.1 (1.7)	47400 (900)	15890 (1000)
Mixture 4	170.6 (0.7)	6.9 (0.3)	36000 (700)	7400	39.2 (3.0)	38600 (1500)	8100 (2470)
Mixture 5	132.9 (3.9)	13.8 (0.4)	50500 (900)	13400	41.3 (2.2)	47500 (900)	18740 (4600)

The results of the study show an increase of the tensile strength and the fracture energy with an increment of the fiber content and with an increment of the fiber length for both, quasi-static and dynamic loading. Observations of the literature can be confirmed, that the tensile strength is positively influenced by the fiber content. However, a positive effect seems to be valid up to a certain length of the steel fiber, which guarantees a good workability. In terms of a good workability and under consideration of material cost a UHPC with longer fibers is preferred to a material with higher fiber content. The application of PVA-fiber reinforcement shows a good performance of the UHPC, although the properties of steel fiber reinforcement with comparable fiber content cannot be reached. The combination of steel and PVA fibers of 1 percent by volume per each leads to a strongly improved fracture energy and a good dynamic tensile strength. In comparison to the mixture B4Q, the tensile strength is in the same range and the dynamic fracture energy could be increased by about 87 %. Figure 6 shows the influence of the variation properties on the dynamic fracture energy.

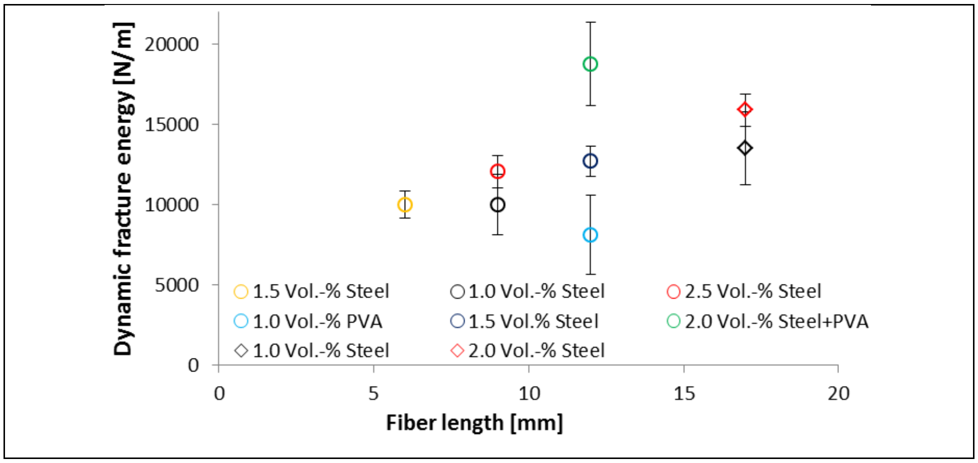

Figure 6. Influence of the fiber content, the fiber length and the fiber material on the dynamic fracture energy

Furthermore, a better behavior under high temperature loading, also present under detonative events, was observed. The loading drove a temperature profile according to the standard temperature curve. After the high temperature loading the samples of the UHPC mixture showed a residual compressive strength of about 15 % with a property in the range of a normal strength concrete, while the normal strength concrete and the UHPC without fiber reinforcement have a residual strength nearly zero.

4. Summary and Conclusions

This paper reports about the development of highly resilient structural material that can withstand extreme loadings due to detonation of high explosives. For reaching this target a layered structure was developed consisting of a concrete core in normal strength reinforced concrete surrounded by a protective layer in ultra-high performance concrete. The material design of the UHPC focusses on the optimization of an existing mixture for a coarse aggregate material (B4Q). Due to the variation of the fiber reinforcement with respect to fiber content, fiber length and fiber material an effective mixture combining best performance properties was determined. The characterization under quasi-static and dynamic loading conditions shows the constructive advantages in comparison to normal strength concrete and standard UHPC. The characterization results in the following conclusions:

- The increase of the fiber length leads to a moderate increase of the quasi-static tensile strength and to a strong increase of the quasi-static and the dynamic fracture energy. The compressive strength and the dynamic tensile strength show no clear effect.
- The fiber material has an influence on the material properties. The mixture with only PVA fibers shows a lower fracture energy and a lower tensile strength compared to a steel-fiber reinforced UHPC with similar fiber content.

- The mixture using a fiber cocktail consisting of steel and PVA fibers leads to the highest values of the quasi-static and the dynamic fracture energy.
- The fiber volume fraction shows an opposite development: For lower fiber lengths, the tensile strength and the fracture energy are influenced positively, leading to higher properties. For longer fibers (> 17 mm), the tensile strength and the fracture energy seems to be influenced negatively due to worse workability and fiber alignment.

In future, an experimental campaign on structural members the effectiveness of the developed design will be evaluated. Realistic loading scenarios on structures with realistic dimensions will be tested in scaled tests. Consequently a higher resistance of the structural members will be realized leading to resilient building structures that are capable to withstand extreme loading scenarios.

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