Analysis of the influence of supplementary cementitious materials used in UHPC on modulus of elasticity

J Fládr¹, P Bíly¹ and T Trtík¹

¹ Faculty of Civil Engineering, CTU in Prague, Thákurova 7, 166 29 Prague, Czech Republic

Abstract. The paper presents the results of static and dynamic modulus of elasticity measurements that were conducted on high-performance concretes with partial replacement of cement by supplementary cementitious materials (SCM). Metakaolin, microsilica and fly ash were used as SCM, the replacement levels were 10 %, 20 % and 30 % of cement weight. The tests were conducted on cylindrical samples 100 mm in diameter and 200 mm in height. Dynamic modulus was measured at the age of 1, 3, 7, 14, 21 and 28 days with the use of non-destructive ultrasound pulse method. Static modulus was determined by destructive compression test. The highest values were reached for fly ash at 20 % and 30 % replacements. Samples containing metakaolin had always lower modulus than the reference concrete. The coefficients for recalculation of dynamic modulus to static modulus were derived as 0.95 for reference concrete, 0.80 for metakaolin concrete, 0.85 for microsilica concrete and 0.90 for fly ash concrete.

1. Introduction
Cement is the most expensive compound of concrete and at the same time its production yields the biggest amounts of greenhouse gases [1]. The research of possibilities of alternative cement substitutions can reduce the costs of concrete production and improve the environment. The important benefit is the exploitation of waste materials as cement replacement, because it also reduces the landfiling. The examples of such materials are microsilica or fly ash. Both these additives can be classified as latent hydraulic ones and therefore they are suitable as supplementary cementitious materials (SCM) [2].

When substituting cement by SCM, it is important to check the mechanical properties of concrete as both their values and time development can be changed. This fact is widely known and supervised in the industrial production. Unfortunately, only the compressive strength is usually observed. In some cases the durability is also considered. Modulus of elasticity is often neglected even in case of concrete without additives. At the same time, the value of modulus of elasticity is very important for the design of structures to serviceability limit states. Moreover, the rate of increase of modulus of elasticity significantly influences the speed of construction process of in-situ cast structures.

2. Experimental methods
In the experimental program, three types of SCM were used: microsilica (labelled as Mic), fly ash (FA) and metakaolin (Met). All these SCM were used as partial replacement of Portland cement by 10 %, 20 % and 30 % of cement weight. The composition of the mixtures is given in table 1. For the reference, the mixture labelled as Ref with no SCM was used.
Table 1. Composition of the mixtures [kg/m³].

| Compound     | Ref  | Met  | Mic  | FA  |
|--------------|------|------|------|-----|
|              | 10 % | 20 % | 30 % | 10 %| 20 %| 30 %| 10 %| 20 %| 30 %|
| Cement       | 800  | 720  | 640  | 560 | 720 | 640 | 560 | 720 | 640 | 560 |
| Water        | 210  | 210  | 210  | 210 | 231 | 252 | 273 | 197 | 184 | 172 |
| Plasticizer  | 30.0 | 30.0 | 30.0 | 33.0| 33.0| 34.0| 32.0| 30.0|     |     |
| Additive     | -    | 80   | 160  | 240 | 80  | 160 | 240 | 80  | 160 | 240 |
| w/b          | 0.26 | 0.26 | 0.26 | 0.26| 0.26| 0.26| 0.26| 0.26| 0.26| 0.26|
| Aggregate 0/4| 730  | 730  | 730  | 730 | 730 | 730 | 730 | 730 | 730 | 730 |
| Aggregate 4/8| 390  | 390  | 390  | 390 | 390 | 390 | 390 | 390 | 390 | 390 |
| Aggregate 8/16| 320  | 320  | 320  | 320 | 320 | 320 | 320 | 320 | 320 | 320 |

Three cylinders (100 mm diameter, 200 mm height) and three 100 mm cubes were produced from each mixture. The values given in the paper are arithmetic averages of three measurements in all cases. The specimens were unmoulded and dynamic modulus measurements were commenced one day after concreting. Further measurements took place at 3, 7, 14, 21 and 28 days. During this time, the samples were stored at laboratory conditions (25 °C, 30 % relative humidity). This is not in accordance with the guidelines for storage of specimens for strength tests [3] which require the relative humidity to be between 95 – 100 %. The authors wanted to avoid the fact that if the samples were stored in water, the pores would be filled by water which would significantly affect the dynamic modulus measurements.

2.1. Dynamic modulus of elasticity
The determination of dynamic modulus was carried out by non-destructive ultrasonic pulse method according to [4]. Pundit Lab (+) device by Proceq company was used together with 54 kHz probes and sonogel improving the contact of probes with the sample.
Before each measurement of velocity of passage of the pulse through the sample, the sample was weighted with 0.01 g precision. The current weight of the sample was used for calculation of dynamic modulus according to equation (1). The measured values were also important for humidity decrease rate control.

\[
E_{\text{dyn}} = \frac{\rho \cdot \left( \frac{v_u}{1000} \right)^2}{k^2 \cdot 1000}
\]  
(1)

In the equation, \( \rho \) is bulk density [kg/m³], \( v_u \) is the velocity of the ultrasound pulse wave [m/s] and \( k \) is the largeness coefficient [-] according to equation (2).

\[
k = \sqrt{\frac{1 - \nu}{(1 + \nu)(1 - 2 \cdot \nu)}}
\]  
(2)

The Poisson ratio (\( \nu \)) was considered as 0.2. The final values of dynamic modulus of elasticity are listed in table 2.

2.2. Static modulus of elasticity
The values were determined by destructive compression tests. Before the main test, it was necessary to establish the value of compressive strength for all types of concrete. The cubic compressive strength, which is important for proper set up of loading cycles, was measured on 100 mm cubes and multiplied by 0.8 to obtain cylindrical compressive strength (in accordance with previous experience of the authors and literature recommendations [5]).
The cylinder bottoms were ground before the tests to secure planarity and collinearity of both bottoms. The specimens were equipped with two independent strain gauges and tested according to [6]. Average results are given in table 2.

3. Results
The time development of dynamic elastic modulus of all the mixtures is given in figures 1 – 3 for particular additives. Reference concrete is inserted for comparison in all the figures. Table 2 summarizes the values of dynamic and static modulus at the age of 28 days. The last row of the table shows the ratio between static and dynamic modulus of elasticity.

![Figure 1](image1.png)

**Figure 1.** Time development of dynamic modulus of elasticity – mixtures containing metakaolin.

![Figure 2](image2.png)

**Figure 2.** Time development of dynamic modulus of elasticity – mixtures containing microsilica.
Figure 3. Time development of dynamic modulus of elasticity – mixtures containing fly ash.

Table 2. Values of dynamic and static modulus of elasticity at the age of 28 days [GPa].

| Modulus | Ref  | Met  | Mic  | FA  |
|---------|------|------|------|-----|
|         | 54.09| 51.34| 55.02| 55.95|
| Dynamic | 51.30| 42.16| 46.76| 48.10|
| Static  | 51.34| 51.34| 55.02| 55.95|
| E_s/E_d | 0.95 | 0.82 | 0.85 | 0.86 |

4. Conclusions
From the results presented in the previous section, following conclusions regarding the changes of values of modulus of elasticity can be drawn:

- The development of dynamic modulus was significant in the first 10 days, later the value was practically constant for all the mixtures.
- Metakaolin reduced the value of dynamic modulus at all replacement levels (10 %, 20 %, 30 %). At the same time, the growth rate was smaller than in case of reference concrete.
- Microsilica at 20 % and 30 % replacement showed the same values of dynamic modulus from the age of 10 days until the end of the measurement. The samples with 10 % replacement had systematically lower modulus than the reference concrete.
- The rate of dynamic modulus growth of microsilica concrete was smaller than for reference concrete at all replacement levels.
- Fly ash at 20 % and 30 % replacement behaved in the same way as the reference mixture. One day value was even higher than for the reference concrete.
- Fly ash at 10 % replacement had lower elastic modulus than the reference concrete during whole course of the measurement campaign.
- The recalculation coefficients from dynamic to static elastic modulus at the age of 28 days were dependent on the type of additive only, not on the replacement level. For the reference concrete the value was 0.95, for metakaolin concrete it was determined as 0.80, for microsilica concrete as 0.85 and for fly ash concrete as 0.90.

Based on the aforementioned conclusions, it can be said that to reach the highest possible modulus of elasticity of concrete with SCM, the best solution is to replace 20 % or 30 % of cement weight by fly ash. An agreement between the dependence of dynamic modulus and static modulus on cement replacement level was observed.

Acknowledgments
This paper was prepared thanks to the support of the Science Foundation of the Czech Republic (GAČR), project “Analysis of the relations between the microstructure and macroscopic properties of
ultra-high performance concretes” (no. 17-19463S).

References
[1] Kara M 2012 Environmental and economic advantages associated with the use of RDF in cement kilns Resources, Conservation and Recycling vol 68 p 21-28
[2] Chylík R and Šeps K 2018 Influence of cement replacement by admixture on mechanical properties of concrete Proceedings of the 12th International fib PhD symposium in Civil Engineering Calorimetry (Prague, Czech Republic: Czech Technical University) Currently in print
[3] ČSN EN 12390-2, Testing hardened concrete - Part 2: Making and curing specimens for strength tests.
[4] ČSN EN 12504-4, Testing concrete - Part 4: Determination of ultrasonic pulse velocity.
[5] Collepardi M 2010 The New Concrete, vol 2, Grafiche Tintoretto p 436 ISBN: 8890377720
[6] ČSN EN 12390-13, Testing hardened concrete - Part 13: Determination of secant modulus of elasticity in compression.