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CONCRETE – FUTURE MATERIAL FOR HIGH PRECISION MACHINES

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ABSTRACT

In previous studies it has been shown that machine parts for high precision applications made of Self Compacting Concrete (SCC) are a promising alternative to those conventionally made of natural stone. Parts with comparable functional surface finish and mechanical properties can be done in shorter time and at lower cost starting from small lot sizes. The developed "ready-to-use" primary shaping process offers vast freedom of design compared to machined natural stone. In the current studies the concrete mixture, the moulding and post moulding processes have been continuously optimised. Now long term stable machine parts can be made with a geometrical deviation / fluctuation in the same range as parts made of natural stone. This article shows major improvements of the properties that have been achieved based on solid concrete beams. An overview will be given for future research of lightweight concrete parts.

Index Terms – precision parts, Concrete, SCC, moulding, curing, flatness, waviness, roughness, surface quality

1. INTRODUCTION

Precision machines are basically constructed with two fundamentally different groups of components. Static components such as machine base frames have a supporting function and must reduce the vibration of the overall system. A large mass is of advantage here. For a wide range of precision machine applications natural stone, for example granite, is the preferred material. Major drawbacks are a long and complex supply chain and high material- and machining costs. In contrast, there are the moving elements, which are characterised by a high stiffness combined with a low mass. Moving parts are mostly made of cast iron, welded and / or machined steel, light metal alloys, ceramics or composite materials. Also here concrete is a promising alternative.

The requirements of high precision machines in regard to geometrical quality and mechanical stiffness are substantially higher than in common applications in civil engineering. The machine frame has to act as a rigid base for a sliding superstructure. The load of the moving slide needs to be taken by the base frame with negligible deformation thus forming an almost perfect guide way. Especially the widely used aerostatic guides are sensitive to local and global geometric deviations since they work with a small air gap of 10 to 15 microns only. Local surface quality characterised by roughness and waviness needs to be below the gap height to avoid a direct mechanical contact of the aerostatic bearing elements. The guiding precision of aerostatic guideways is depending on the global flatness and the long-term stability of the geometry. To address these requirements it needs a manufacturing process that guaranties smooth and flat surfaces and specifically geared and modified concrete mixtures.

The technology for achieving high precision solid parts with smooth and levelled surfaces in micrometre range with standard SCC in a mould process has been demonstrated by the authors previously [2].

2. SOLID MACHINE PARTS MADE OF CONCRETE

Experiments and measurements for the qualification of the methods and materials have been done with tall concrete beams with a rectangular cross-section. They show a high sensitivity in geometry changes caused by internal chemical and physical processes as well as by external loads. As a mould a reinforced frame design was fixed on top of a rigid plane natural stone plate forming the reference plane for the functional surface of the part to mould. Polyethylene foil was applied as a barrier layer to protect the natural stone and to guarantee a low surface roughness [1]. Several tests of different concrete mixtures, casting technologies and curing processes were done systematically. The beams' local surface quality, flatness deviations and time dependent deformations were observed over time. The mechanical and thermal properties of the mixtures were tested with separate standard material tests.

2.1 Material properties of modified self-compacting concretes (SCC)

SCC mixtures were projected and modified to achieve optimal material properties comparable to natural stone. The development was done in three ways: Utilization of high powder content, a viscosity modifying agent and both, higher powder content and a viscosity modifying agent in combination [3]. A PCE superplasticiser ensures the viscosity of the SCC mixtures for a good mould filling behaviour and processing stability. The thermal expansion coefficient was adjusted equivalent to steel, to allow for part integration without thermal stresses. The concrete's material properties have been optimised for the target application. The curing time has been decreased. The achieved strength and stiffness values of ready-to-use (cured) concretes can be seen in table 1.

Table1: Cured SCC properties compared with natural stone and standard concrete [2]

property	unit	natural stone	standard concrete	SCC I	SCC II
compr. strength	[N/mm²]	250 – 360	5 – 55	110.1	109.2
flexure strength	[N/mm²]	10 – 35	2 – 8	8.1	7.7
Young´s modulus	[kN/mm²]	60 – 95	21.8 – 34.3	45.4	44.4
density	[g/cm³]	2.90	2.0 – 2.6	2.48	2.47
shrinkage	[µm/m]	---	≈ 350	230	240

A huge improvement of the compressive strength by a factor of three in comparison to standard concrete was achieved. The flexure strength of SCC I and II is comparable to the best standard concretes. The stiffness was increased by 60%. There is still a difference to the absolute numbers of the material properties of natural stone. This is of minor importance since it can be compensated by enlarged dimensions in the design process. A major progress has been made in the reduction of the shrinkage of about 35% in comparison to standard concrete. This enables the development of concrete parts with highly precise geometry and stable dimensions.

2.2 Short range quality of moulded surfaces

2.2.1 Roughness of concrete beam samples

Roughness measurement was done by use of a standard roughness meter. Based on at least 10 measurements taken at different paths the standard deviation of the roughness of each beam was calculated.

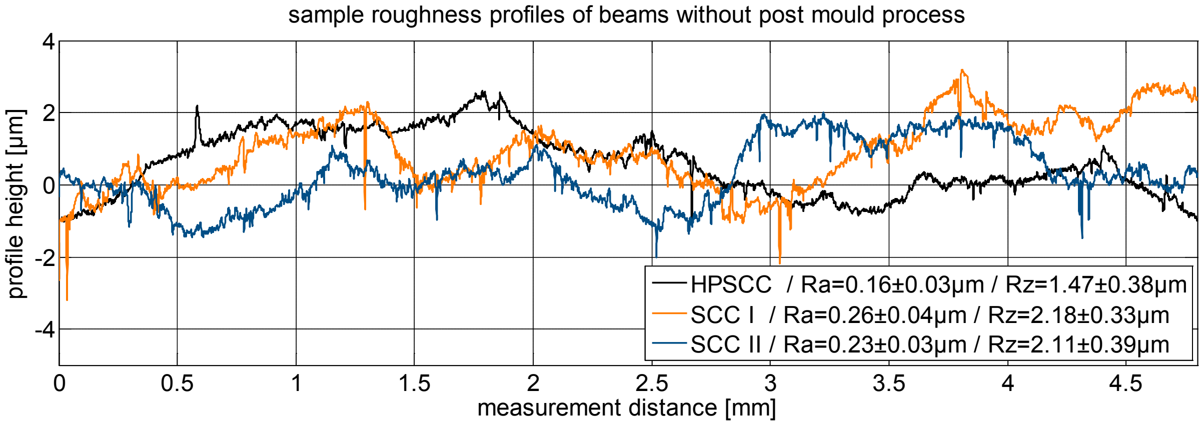

Figure 1: roughness of special SCC surfaces without post processing

The homogeneity of the roughness across the entire beam surface is characterised by means of the standard deviation. Figure 1 displays the unfiltered roughness profiles of samples produced in a direct mould process without any post treatment. The samples for the measurements shown are made of a commercially available High Performance Self Compacting Concrete (HPSCC) and the specifically developed SCC I and II. The values are 30 % lower than those reached in earlier studies with standard SCC and superior to those of machined natural stone based slide ways for air bearings (R_z = 5.2 µm, R_a = 0.56 µm) [2].

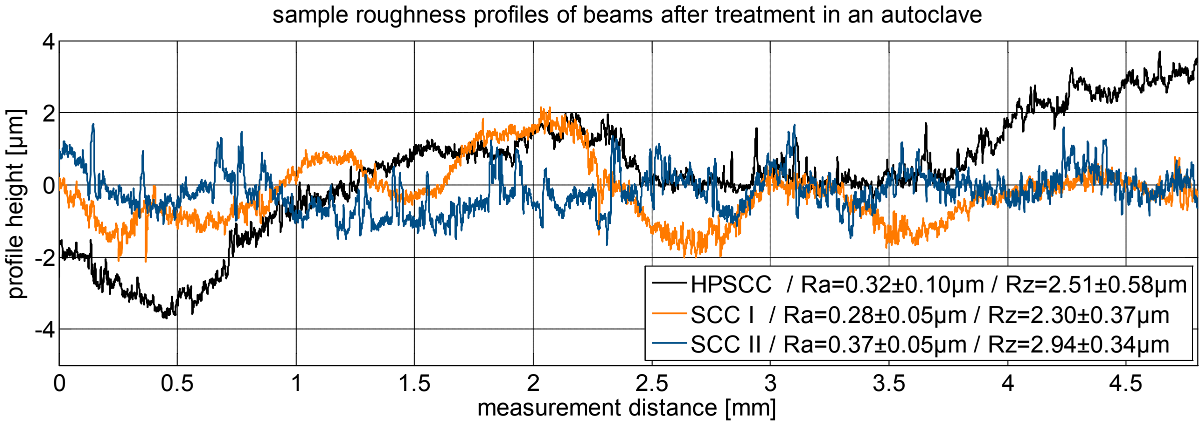

Figure 2: roughness of special SCC surfaces with post processing in an autoclave

It is state of the art to treat the concrete parts in an autoclave process. Autoclaving of concrete parts is equivalent to an artificial aging process to accelerate the curing process. During the autoclave process crystals are blooming out of the surface. The roughness value increases depending on the mixture in a range of 10% up to 50% still remaining significantly below the target roughness.

2.2.2 Waviness of moulded concrete surfaces

The HPSCC sample test beam has been moulded on a foil with a thickness of 100 µm and shows a relatively strong waviness with a height of ≤ 7 µm and a periodicity near 8 mm.

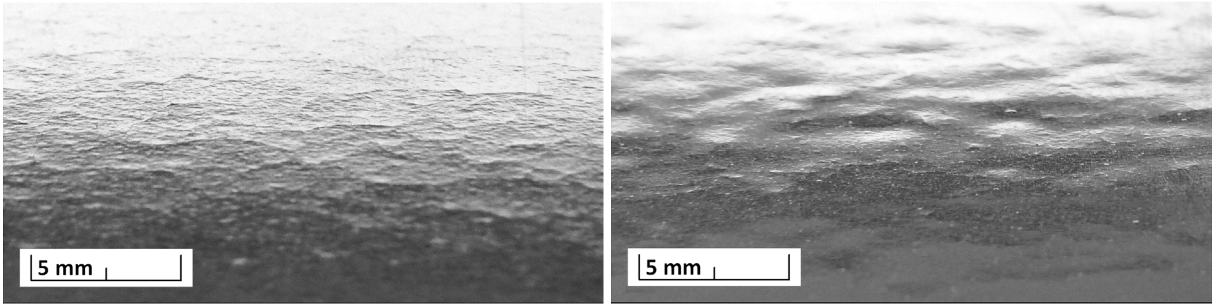

Figure 3: waviness of concrete surfaces moulded on different barrier foils (left: 20 µm barrier foil, right: 100 µm barrier foil)

The SCC I and II beams moulded on a 25 µm foil have smooth surface ripples with a height of ≤ 4 µm and a periodicity near 8 mm (cf. roughness profile plots in figures 1 and 2). Pictures are shown in figure 3. The waviness is caused by inhomogeneity of the barrier foil's stiffness and thickness. The search for high quality foil that meets all requirements is still part of on-going studies.

2.3 Long range quality of moulded surfaces

Flatness measurements have been used to characterise the global surface quality. Even if the parts' horizontal surfaces are moulded on a best flat standard plane they turn into a bow shape against gravity during the curing. This buckling effect is a result of chemical and physical processes. The maximum height of the buckle is in close correlation with the shrinkage value. The height can be used as a simple measure for the state of the curing process.

2.3.1 Time depended flatness of precision concrete surfaces [1]

The buckling of the moulded parts is changing over the curing time. During a time period of over 100 days the deflection behaviour of the beam surfaces was measured with an autocollimator-mirror-arrangement on a weekly basis. The geometrical stability was compared with a natural stone reference beam made of granite. Figure 4 (left) shows the height profiles of the sample beams. The curing process took 6 weeks after moulding till the parts reached a steady state. In comparison to former experiments this is an improvement of 30% in stabilization time. The maximum deformation of the test beams is about 80 µm which is an improvement of over 40% compared to previous results achieved with standard SCC [2].

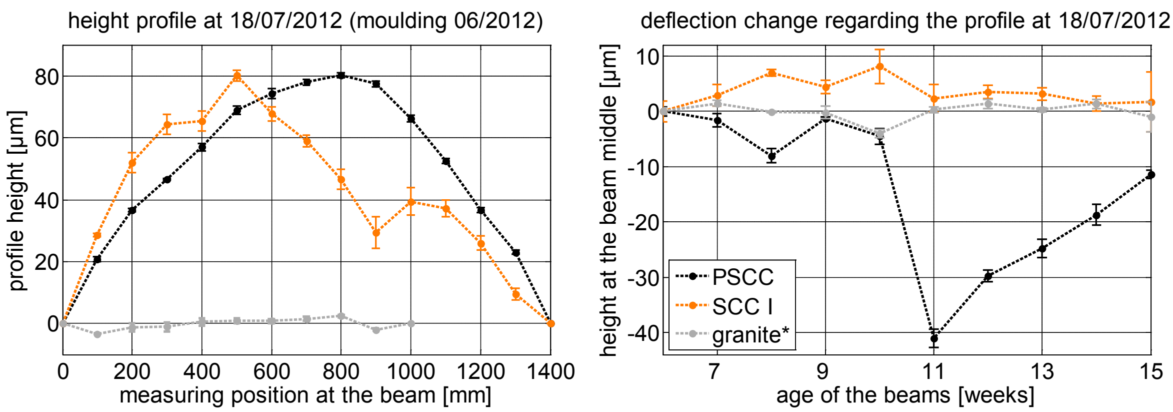

Figure 4: height profiles of sample beams 2012 after 6 weeks stabilisation time (left) and the time depended deflection in the middle of the beams with regard to the profiles at week 6 (right)
**granite reference beam with dimensions 100 x 130 x 1030 [mm³]*

The absolute flatness deviation is of minor interest for precision machine parts. Because these small deviations of the absolute flatness can be corrected, compensated or prevented by special mould geometry. The main challenge for precision engineering parts is the long term stability of the geometry. In figure 4 (right) the deflection changes at the beam surface centre are plotted over a period of 10 weeks with regard to the height profiles shown in the figure to the left.

In the first 4 weeks both concrete beams show a good long-term stability comparable to the granite reference beam. The SCC I beam is not changing over the whole time of observation. To investigate the influence of humidity, the beam made of Polymer modified Self-Compacting Concrete (PSCC) and the granite reference beam were stored in an atmosphere with 100% relative humidity for two days in-between the measurements taken at week 10 and week 11. The deflection of the PSCC beam decreased rapidly by 40 µm, but the granite beam did not show any reaction to this treatment. This is a weakness of concrete parts that needs to be addressed for wet condition applications just like machine tools. The concrete parts have to be protected with moisture barrier layers like epoxy resin or glass. As an alternative the parts can be used in continuously wet surroundings (e.g. in a water bath of cooling fluid or fluids to wash away the cuttings).

2.3.2 Flatness behaviour in the context of autoclave treatment

In figure 5 results of a test series for the investigation of autoclave treatment are shown. Two equal beams of different mixtures were moulded at the same time. One beam of each mixture was treated in an autoclave for one week. The maximum deflection of both SCC II beams is in a range of 30 µm which is an improvement of more than 75% compared to previous results [2]. The deformation of the HPSCC beams stopped within 60 µm and 70 µm.

Time dependent deflection changes are most relevant to determine the quality of concrete parts and mixtures. The zigzag profiles of the flatness deviations in figure 5 (left) are the result of the overlain waviness shown in figure 3. So the absolute deviations are afflicted with a high uncertainty. However, a relative profile measurement with highly reproducible contact points cancels out the positioning uncertainty. This allows for the investigation of the beam middle height deformation over a long time period. To avoid systematic uncertainty the measurements since January 2013 were done by a specifically developed automatic straightness measurement system. The standard deviation / uncertainty of the measurement values is decreased by one magnitude (cf. error bars of figure 4 and 5).

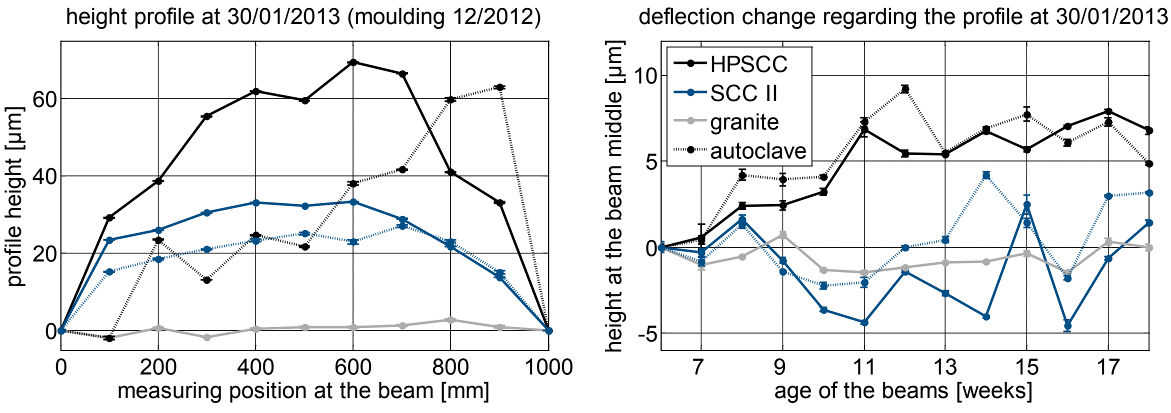

Figure 5: height profiles of sample beams after 6 weeks stabilisation time (left) and the time depended deflection behaviour in the middle of the beams in respect to week 6 (right)

All the beams shown in figure 5 (left) are characterized by a good long-term stability with flatness deflections (right) in the same range as the granite reference beam. A relation between surface deflections and the autoclave treatment concerning flatness deviations could not be found.

3. CONCRETE FOR LIGHTWEIGHT CONSTRUCTION

Future studies will address complete machine concepts with high mass base frames and lightweight moving parts based on concrete. The new approach is to develop thermally balanced machine concepts for high precision applications with large dimensions. It can also be applied for the replacement of cast iron, welded and / or machined steel, light metal alloys, ceramics or composite materials for parts in processing machines and machine tools.

The achieved know how for precision frame parts can be used to merge lightweight design with a high level of integration while still sustaining the demanded flatness. The parts of a previously developed lightweight demonstrator element series shown in figure 7 are characterised by three main points:

- Support structure with high stiffness (stable honeycomb structure)
- Smooth and levelled functional surface with a reflective quality (directly moulded air bearing suitable surface)
- Integrated components as coupling to peripheral elements (legs made of steel)

The feasibility of producing lightweight parts with nearly the same specific stiffness as cast iron parts is demonstrated. The next step is to investigate and secure the endurance strength of concrete parts and to develop suitable design guidelines.

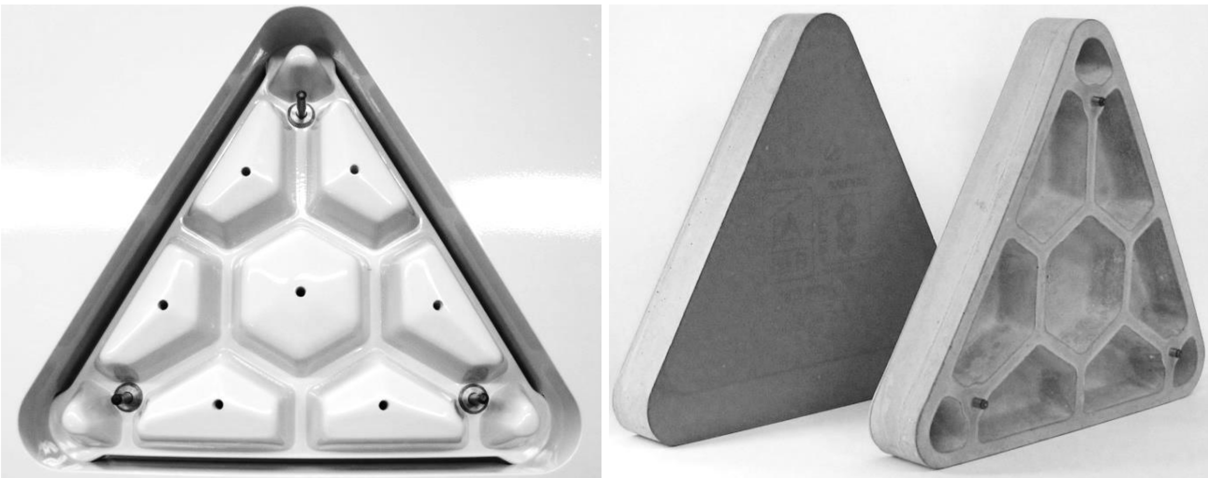

Figure 7: series of demonstrators of a machine frame part with reflecting functional surfaces and complex geometry in lightweight design (right) and respective moulding (left)

4. CONCLUSIONS

Concrete parts having functional surfaces with a roughness appropriate for aerostatic guideways can be created by a "ready-to-use" mould process. Latest concrete compositions show excellent long-term stability and mechanical properties comparable to natural stone. Test beams with an absolute maximum straightness deviation of 30 µm / m were moulded. After the concrete has cured, the long-term stability resembles the behaviour of granite. The research is still focusing on the sensitivity to humidity and other environmental influences to create parts that are suitable for normal environmental surroundings beyond the laboratory. If the production of lightweight concrete parts with fail-safe endurance strength is successful thermally balanced integral machine concepts can be realized for measurement and manufacturing applications.

ACKNOWLEDGMENTS

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REFERENCES

[1] C. Hahm, R. Theska, K. John, A. Flohr, A. Dimmig-Osburg, "Concrete based parts for high precision applications," Proceedings of the 13th International Conference of the European Society for Precision Engineering and Nanotechnology, Berlin, Vol. 1 p.p. 171-174, ISBN 13: 978-0-9566790-2-4, 2013

[2] M. Berg, R. Bernau, T. Erbe, K. Bode, R. Theska, "Primary shaping of smooth and level guideway planes for high precision applications," Proceedings of the 10th International Conference of the European Society for Precision Engineering and Nanotechnology, Delft, Vol. 1 p.p. 279-282 ISBN 13: 978-0-9553082-8-4, 2010

[3] H. Okamura, M. Ouchi, A. Skarendahl, Ö. Petersson, "Self-compacting concrete: development, present use and future", Proceedings of 1st int. Rilem symp. on SCC, RILEM Publications SARL, Bagneux, pp. 3-14, 1999

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