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AUTOMATION OF SMALL SAMPLE POSITIONING FOR MECHANICAL TESTING IN HOT CELLS

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Abstract. The main objective of this paper is to propose an improvement and automation of the current mechanical testing procedure of concrete and rock samples in hot cells, i.e. in laboratories designed for radioactive sample testing. The paper describes the effect of radiation on the different components of concrete and consequently on the concrete itself. To give a general idea of sample handling and hot cell operations, safety precautions are prescribed which significantly prolong and complicate the handling of a radioactive rock sample. Video recordings of the tests were used to analyse the progress of the tests. The main issues were the placement of samples off the axis of the compression test machine, sample curvature, compression test machine design and poor recording of sample deformation. New centring stops were introduced to improve the handling of the specimen when placed in the test machine. Additionally, the use of image processing was proposed to evaluate the correct placement of the sample in the test machine. These improvements should lead to easier sample handling and correct results which will serve as a good basis for subsequent numerical analyses.

Keywords: Mechanical testing, image processing, hot cells, radioactivity, concrete, rock.

1. Introduction

Ensuring the long-term functionality of critical structural elements of nuclear power plants is essential for the safe operation of these facilities not only in the Czech Republic but also worldwide, especially if the lifetime of nuclear power plants is to be extended. With increasing energy consumption, it is necessary to keep these facilities in operation for as long as possible, while further construction or expansion of existing nuclear power plants is of course being considered. In addition, there are also plans to build small modular reactors. In all these cases, concrete will also be used to shield radiation. Therefore, the actual condition of shielding concrete in nuclear power plants is currently being evaluated.

The main effect on the cement paste is gamma radiation [1, 2], which causes a loss of free water, which subsequently leads to shrinkage of the cement paste [3] and also radiolysis of the water [4, 5]. The main effect on the aggregate is neutron radiation, which causes defects in the crystal lattice [6, 7]. These defects accumulate and lead to the so-called RIVE (radiation induced volumetric expansion) – swelling of the aggregate. This causes significant stresses in the rock, resulting in internal tension and subsequent cracking [1, 2, 8]. Long-term exposure to radiation thus causes a reduction in the compressive strength of concrete by up to 50 % and a reduction in tensile strength by up to 75 %, while the modulus of elasticity can decrease by up to 25 % [9]. The present work is focused on the mechanical testing of aggregates in hot cells at the Research Centre Řež. The primary aim is to identify systematic errors in the compressive testing of samples in hot cells. This is achieved by comparing the resulting load curves with video recordings of the tests.

This research is also developing an affordable device for use in hot cells, leveraging image analysis. The aim is to develop and programme a custom system that will be able to automate the process of detecting and aligning concrete specimens during compression testing, which is key to ensuring uniform stress distribution.

The handling of the irradiated sample is very complicated for safety reasons and therefore time consuming, which increases the final cost of the testing, which also includes the time of exposure of the samples to irradiation in the reactor and the subsequent disposal of the samples as radioactive waste. The sample can be handled only by manipulators. For these reasons, as well as for limited availability of free positions in the reactor used for irradiation, the number and size of the samples to be tested is significantly limited. Each sample is therefore unique and the test results are taken as a final value without generating statistics. It is therefore essential that the load tests are performed correctly and that the results are meaningful and can be used for subsequent numerical analyses. The elimination of unnecessary errors and imperfections in the testing of irradiated samples is the aim of this paper.

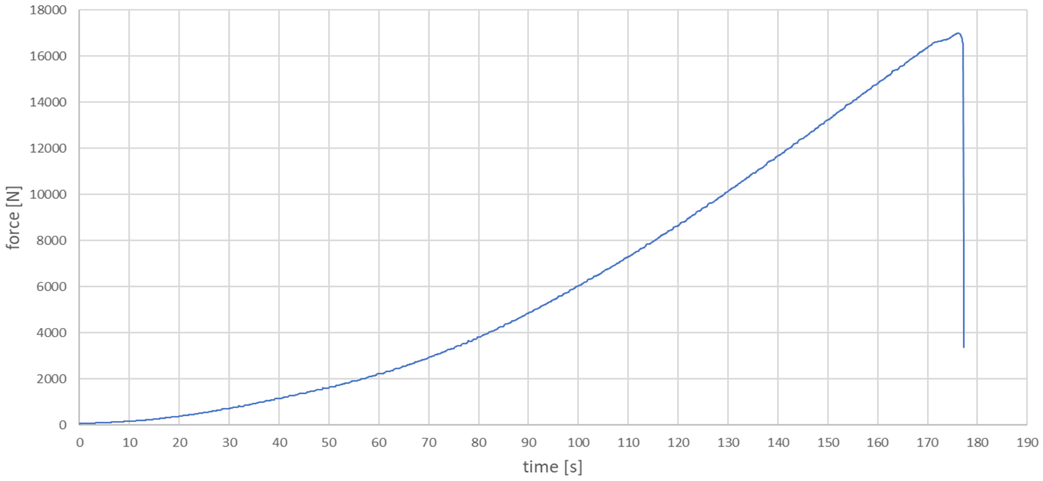

Figure 1. Graphical representation of the dependence of the loading time on the sample with off-centre placement.

2. Issues of sample storage in hot cells

Hot cells (HC) are specialised laboratories designed for the testing of highly radioactive materials. a total of ten such chambers and one half-hot chamber are operated in the controlled area of the Research Centre Řež [10]. The handling and testing of samples in hot cells presents a number of specific challenges.

Sample handling is complicated mainly because of the sample size. The sample size is limited and therefore the sample dimensions cannot be changed. The testing of concrete and aggregate is performed on aggregate cylinders with a height of either 1 or 2 cm and a diameter of 1 cm, or alternatively, cylinders with a height of 6 cm and a diameter of 4 cm for concrete samples. These dimensions were chosen with the technical limitations of the HC and reactor facilities at Řež in mind. The specimen is gripped in the clamps by the manipulator. The manipulator is equipped with a mechanism that allows the attachment of extensions and tweezers of varying dimensions. The handling of the sample is monitored through a lead glass viewing window and also by a camera located in the HC. However, this camera is often located behind the specimen. This causes the operator to move the manipulators in the opposite direction to that seen on the camera. This can sometimes be confusing and requires even more operator concentration. The sample is situated at a distance of several metres from the operator, and it is particularly challenging to position the sample in the centre of the compressive test machine without any deviation from the test machine's axis.

By purchasing conventional cameras, we want to simplify and to make more efficient the positioning of samples into the compressive test machine located in the hot cells using automated image processing. This analysis will allow precise control of the sample position, reducing time and the possibility of manual alignment errors, and ensuring uniform loading during testing. Additionally, the cheaper, commercially available cameras are easy to maintain and quickly replaceable when needed, which keeps instrument operating costs to a minimum and increases the reliability of results.

In the work presented here, we found two major errors, namely, non-centric sample fitting and uneven sample bases. The impact of these errors on the results will be described in the subchapters "Sample placement" and "Uneven bases".

2.1. Sample placement

The correct performance of the compression test of a sample much smaller than the machine's loading platens depends especially on the accurate placement of the sample in the centre of the compressive test machine. If the specimen is placed off axis, uneven loading is imposed, which can lead to failure on the overloaded side. Initially, the specimen is loaded on both bases and as the tension increases, the steel loading platens slightly rotate. This increases the pressure on one side of the specimen, which can lead to failure. To illustrate this problem, a test was performed with the specimen placed off the axis of the compressive test machine.

A sample of aggregate was placed in the compressive test machine off its axis. The sample was 1 cm in diameter and 2 cm in height. The failure of the sample occurred at a load of 17 kN and a time of 177 s, see Figure 1.

It is evident from the test that the sample was placed off the axis of the compressive test machine. The specimen has a horizontal bases and was therefore loaded evenly from the start. During the test, the steel loading platen was gradually rotating for 112 s (Figure 2 and Figure 3), which is caused by the sample being placed off the axis of the test machine. Subsequently, the curve grows linearly until the first cracks appear (Figure 4), which occurs just before the specimen collapses on its overloaded side (Figure 5).

In all tests where the specimen is placed off the axis

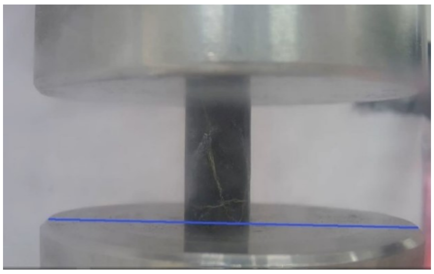

FIGURE 2. Placing the sample in the test machine, time 0 s.

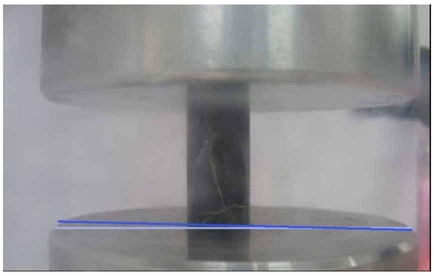

FIGURE 3. Steel loading platen rotation, time 112 s.

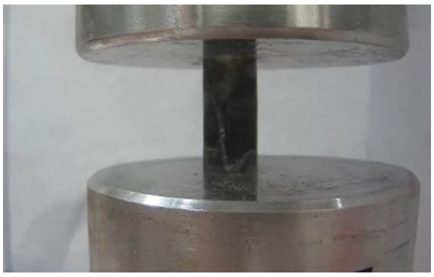

FIGURE 4. First crack, time 170 s.

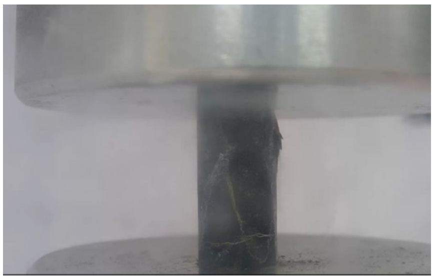

FIGURE 5. Sample failure, time 175 s.

of the compressive test machine, the specimen is damaged due to placement of the sample. The rotation of the steel loading platen is through the specimen, i.e. the platen does not rotate until the specimen is loaded. As the platen rotates, both sides are deformed equally, but along a different length of the specimen edge, resulting in a different relative deformation and therefore a different stress along the edges of the specimen. The force acting on the specimen is shown in Figure 6.

Even for a very small sample placement off the machine's axis, large stress changes occur across the sample cross-section as the core of the cross-section for a 10 mm diameter specimen is only a 2.5 mm diameter circle. This observation also confirms that only minor excentric loading suffices for an uneven loading. The small inaccuracy due to the positioning would not play such a critical role on a normal concrete cube with an edge of 150 mm, but it is significantly more crucial for the 10 mm specimens.

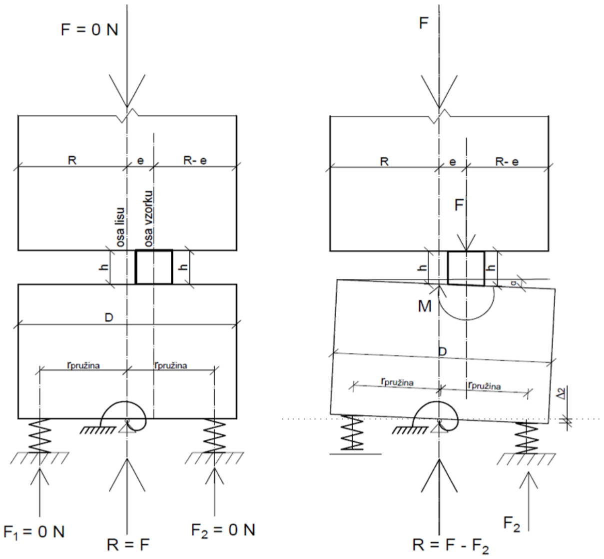

FIGURE 6. Representation of the force acting on a specimen placed off-axis.

2.2. UNEVEN BASES

It is also important to observe the flatness of the sample bases on the sample. If the specimen bases are not parallel, or if the specimen is slightly skewed during specimen preparation, uneven loading will also occur. The loading of the specimen would initially be on the elevated edge of the specimen where the stress concentration would occur. As a result, the sample may fail at this edge, which could lead to either its collapse or the chipping of the sample's edge, causing the bases to become horizontal. Once one edge was damaged, the loading would begin to propagate to the entire specimen, but due to the different stiffnesses, further complications would arise and eventually failure would occur.

A sample with a height of 1 cm and a diameter of 1 cm was selected for the test. The failure of the specimen occurred after 55 s under a load of 2.8 kN, see Figure 7.

The sample has uneven bases, as can be seen in Figure 8. The load curve can be divided into several parts. For the first 20 s of the test, the loading platen is being rotated (Figure 9 and Figure 10) and therefore the curve has a convex shape. Subsequently, the specimen is loaded to almost the entire surface of the base, there is no further rotation of the platen. The curve has a linear shape until 53 s, during which time the edge of the sample is overloaded. At 53 s, the raised edge of the specimen is crushed (Figure 11) and the first cracks appear along the height of this

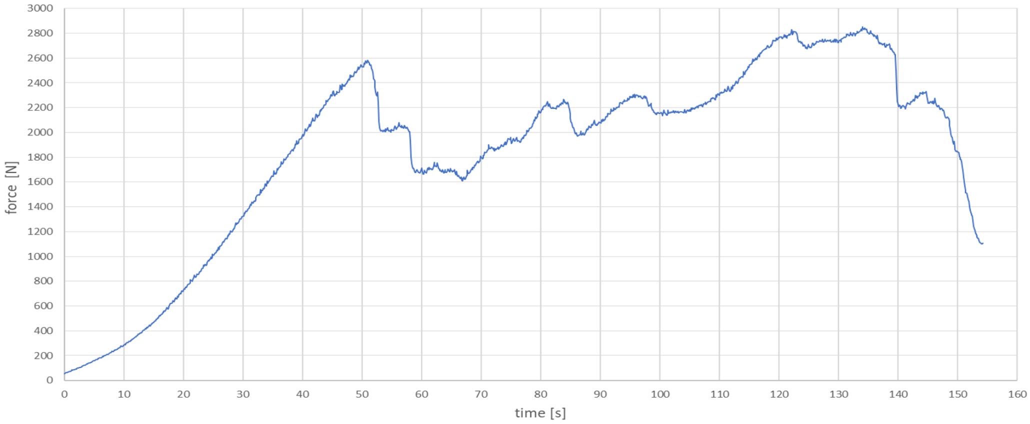

Figure 7. Graphical representation of the dependence of loading time on a sample with uneven bases.

edge. Then the load increases again, the specimen is at this point loaded over the entire surface of the base. The increase in load is no longer linear, as cracks have already formed, and new cracks are being added (Figure 12 and Figure 13). The sample failure occurs at 135 s (Figure 14).

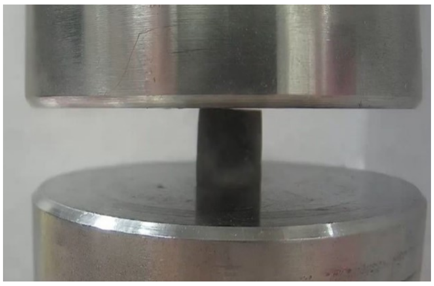

Figure 8. Placement of the sample in the test machine, uneven sub-states uneven bases.

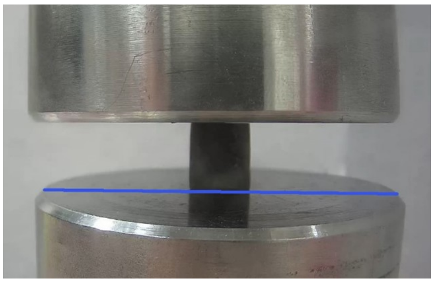

Figure 9. Sample, time 0 s.

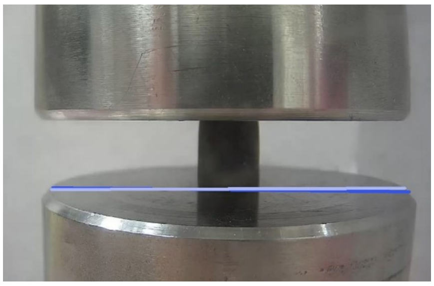

Figure 10. Steel loading platen rotation, time 20 s.

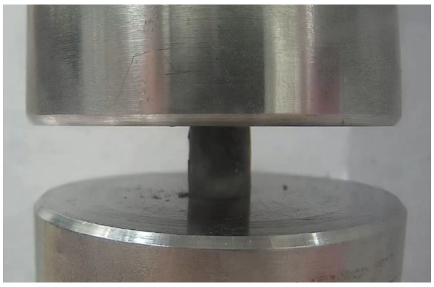

Figure 11. Crushing of the raised edge of the sample, time 58 s.

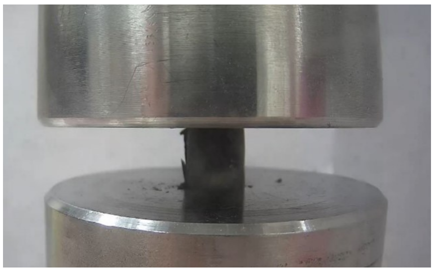

Figure 12. Crack expansion, time 97 s.

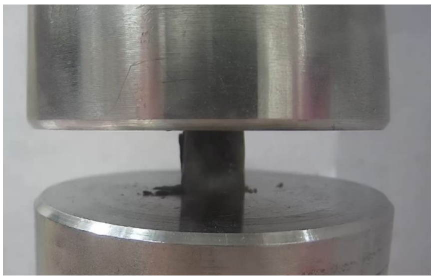

Figure 13. Crack expansion, time 120 s.

The platen is rotated over the edge of the sample, with all the load applied to the edge of the specimen, which causes high stress. Additionally, a moment is applied to the edge of the specimen, as can be observed in Figure 15. The rotation of the loading platen occurs through the specimen, as the edge of the specimen is situated at a relatively small distance from the bearing, and thus a relatively large force is required.

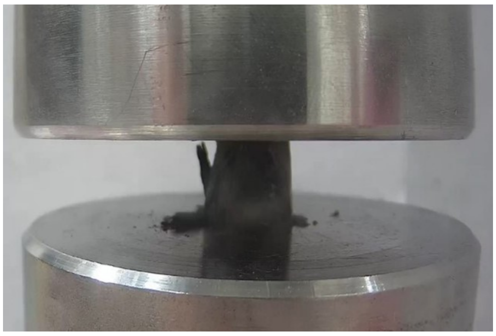

Figure 14. Sample collapse, time 135 s.

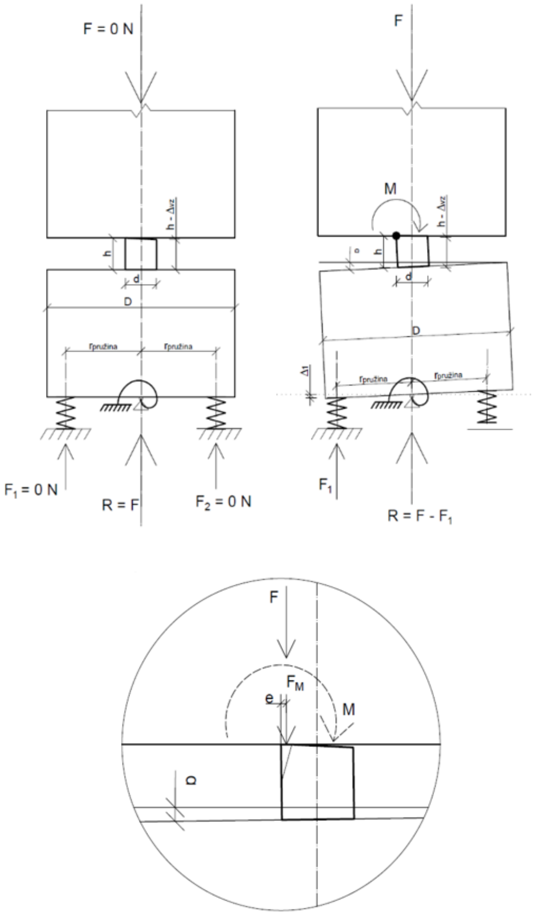

Figure 15. Representation of the force acting on a specimen with uneven bases.

3. Design and control of sample seating

3.1. Mechanical stop for precise sample placement

In order to simplify, speed up and enhance the handling of the sample in the hot cell, a range of products are being developed to adapt to the specific requirements of the test. In this case, the focus is on placing the sample in the axis of the compression test machine, for which centring stops are used. These stops are designed to allow easy handling even within the hot cells.

A static stop was initially developed to support the specimen throughout the test. However, due to the small sample size, this could potentially affect the test results. Therefore, a movable stop was designed (Figure 16), consisting of two parts: a movable part with a handle and a counterpart to ensure its linear motion. The stop moves along two grooves, which provide greater stability and minimise the risk of rotation around a single point.

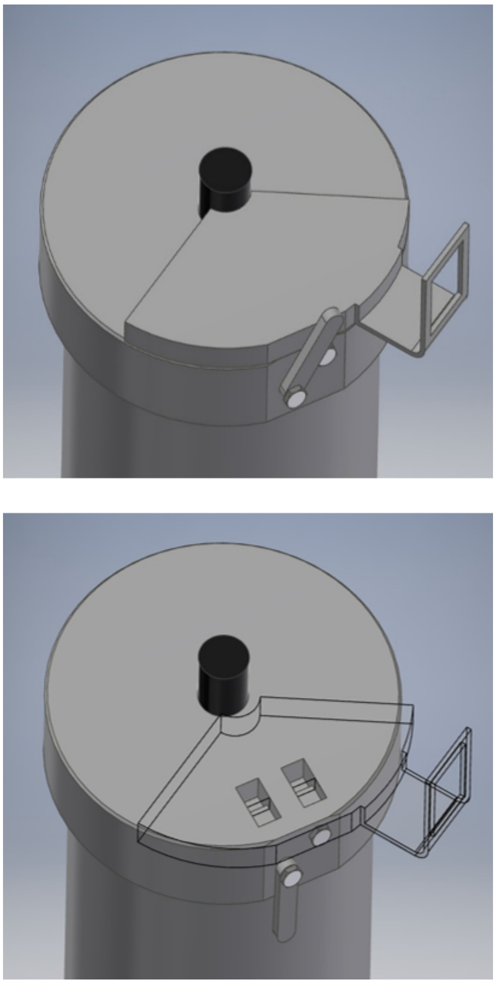

Figure 16. Movable centering stop with sample placement on the centre (top) and during the loading process (bottom) down.

The movable component is designed with a handle for easier manipulation with a manipulator, while the fixed component of the loading platen is equipped with a fixation handle to secure the position when placing the sample. After the sample has been placed in the locked stop, it is preloaded. To minimise the impact of specimen support on test results, the stop is displaced and retracted after preloading. This permits specimen deformation in all directions, thereby ensuring that test results are not influenced by the support. Furthermore, as part of the process optimisation, the steel loading platen with ball seat is being redesigned to be relocated from the lower to the upper position, which should facilitate more uniform sample loading.

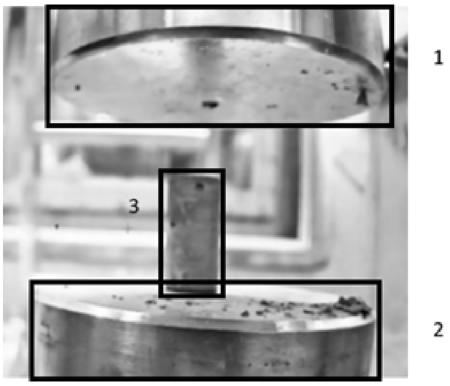

FIGURE 17. Image obtained by one of the cameras, 1-upper loading platen, 2-lower loading platen, 3-concrete sample.

FIGURE 18. Detection of sample location using vertical line detection – a) original image b) after preprocessing c) after final processing.

3.2. CONTROL OF SAMPLE POSITIONING BY IMAGE PROCESSING

An image processing system was created to detect unevenness in the bases of the specimen and to evaluate any off-centre positioning of the concrete specimen relative to the test machine's axis. Optimal camera placement was determined to ensure accurate data capture, with two cameras positioned perpendicular to each other to capture both upper and lower platens as well as the sample (Figure 17).

A Python-based program was developed to process the captured images (Figure 18), allowing for precise extraction of the sample's position and rotation. This program applies image processing techniques to calculate the alignment and centering of the sample, thus ensuring accurate and reliable setup for compression testing.

4. CONCLUSION

The main contribution of this paper is related to improvements of the compression testing of concrete and aggregate samples in hot cell environment. The improvement could be achieved by simplification of sample handling, which could also be achieved through the use of image processing.

Two weak points have been identified which needed to be improved. One is the unevenness of the sample base faces when the top and the bottom faces are not parallel. This leads to uneven loading tested samples. The steel loading platen has to be inclined to match the sample shape to get even load distribution. However, during this rotation the steel loading platen is pressing just one edge of the specimen, which might cause its damage. The sample is then broken at lower load level than perfectly shaped sample. The second factor which had to be considered is the position of the sample in relation to the axis of the compressive test machine. The misalignment also causes uneven loading on the sample. For this reason, a centring stop is designed to ensure that the specimen is positioned in the centre of the press.

Using carefully positioned cameras, it is possible to monitor the entire test process and then analyse details of the sample position relative to the test machine's axis. This not only allows us to check the exact placement of the sample in the test machine, but also to analyse and compare the measured values retrospectively with the visual record of the test. Image analysis in this way eliminates the risk of human error during sample settling and contributes to smoother and better documented tests, which is essential for efficient and consistent interpretation of results.

The implementation of these improvements will facilitate the handling of samples, whilst also ensuring the reliability of the test results, which will serve as a basis for subsequent numerical analyses.

Acknowledgements

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