AN AUTOMATED TEST METHOD FOR DENSITY IN THE SATURATED SURFACE DRY STATE (SSD) OF POROUS GRANULAR MATERIALS

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ABSTRACT

The use of recycled C&DW as aggregates for concrete or similar applications usually involves a careful design of the mix proportions which is based on the attempt to densely pack the graded aggregates such, that no excessive amounts of binder is needed to fill the interstitial spaces, on the other hand assure a good workability of the mix. Because of the required accuracy in proportioning, however, the individual constituents of the mix are added according to their mass. The calculation of the mix proportion therefore requires detailed information on the density of the constituents.

Recycled aggregates usually have a higher porosity than natural aggregates, and therefore their apparent density varies over a wider range when their moisture content changes, e.g. due to preceding exposure to the atmosphere, rain or a treatment. Therefore, it is mandatory to determine the density of corresponding aggregates at different moisture states, for example in a dry state, a water saturated state or intermediate moisture state. The experimental procedures for the determination of the so called saturated - surface dry state (SSD) are complicated and time consuming, the emerging results are subject to important scatter. Different attempts have been made to introduce more reliable test methods.

Keywords: Density, saturated surface dry, test method, drying rate, porosity, water content

1. INTRODUCTION

The amount and grading of aggregates for concrete or similar applications usually involves a careful design of the mix proportions which is based on the attempt to densely pack the graded aggregates such, that no excessive amounts of binder is needed to fill the interstitial spaces, on the other hand assure a good workability of the mix and a sufficient strength and durability of the hardened concrete. Because of the required accuracy in proportioning, however, the individual constituents of the mix are added according to their mass. The calculation of the mix proportion therefore requires detailed information on the density of the constituents. For porous materials, e.g. some types of aggregates, it is vital to consider the porosity of the aggregates which may contain various concentrations of pore water, resulting in an apparent density which then depends on the moisture state of the aggregates.

This is of particular importance when recycled aggregates from construction and demolition waste (C&DW) are considered. Recycled aggregates usually have a higher porosity than
natural aggregates, and therefore their apparent density varies over a wider range when their moisture content changes, e.g. due to preceding exposure to the atmosphere, rain or a treatment. Therefore, it is mandatory to determine the density of corresponding aggregates at different moisture states, for example in a dry state, a water saturated state or at intermediate moisture states.

In the characterisation of the density of porous granular materials the dry density is easily measured after oven drying of the material to constant weight. In contrast, the density in the water saturated state is more difficult to assess: Saturation of porous materials involves a ponding of the materials in water, either at atmospheric pressure, under vacuum or at high external pressure. Subsequently, the mass of the saturated granular materials must be recorded. Fine grained materials, however, offer a huge external surface area at which water films are adsorbed, also in interstitial voids, water is held. These water films must be removed without changing the saturation of the grains, i.e. a saturated but surface dry condition (ssd) must be achieved.

The standardized experimental procedure for the determination of the so-called saturated but surface dry state (SSD) [1] is complicated and time consuming, the emerging results are subject to important scatter. Different attempts have been made to introduce more reliable test methods [2,3,4].

In the following a fully automated test method to derive the density of porous granular materials in the saturated – surface dry state from a drying experiment is described. After the experimental set up is explained test results are presented for different granular materials such as crushed clay bricks, calcium silicate bricks, crushed concrete, river gravel as well as mixes thereof in different grain sizes. The observed results of the proposed method are compared to density characteristics as derived from standardized test methods, and recommendations for the application of the new method are given.

2. THEORETICAL BASIS OF TEST METHOD AND EXPERIMENTAL SET-UP

2.1 The drying behaviour of porous materials

Different types of water can contribute to the mass of moist materials and thus also to the apparent density: Water films adsorbed to the external surface of granular materials as well as bulk water held in interstitial pore spaces of fine grained materials prevail after extensive wetting of materials, e.g. subjected to rain. Prolonged exposure to liquid water leads to capillary absorption in the internal interconnected capillary pores, in fine pore spaces the adsorption of water films from water vapour finally results in capillary condensation.

Upon drying of the porous materials the water will be liberated by different mechanisms and at different drying rates with time. For constant drying conditions, i.e. constant ambient temperature and relative humidity, water held at the external grain boundaries or in interstitial pore spaces between individual grains evaporates from a free surface at a constant drying rate until a dry surface has been reached. Then, a second drying regime is observed which is controlled by the capillary flow of water in the internal interconnected capillary pores of the materials, i.e. water is carried by capillary action to the surface, where it will then evaporate. In this stage, the drying rate decreases linearly with time. Depending on the capillary pore system of the material tested, this period may be rather short or even vanish, when the evaporation front of the water moves inward into the material. In this state, the transport of water molecules to the surface is controlled by vapour diffusion and a non-linear decrease of the drying rate with time is observed until all free water has been liberated.
For the proposed test method the transition from the first drying regime, i.e. the liberation of water at constant drying rate to the second or third drying regime, when the drying rate decreases with time, is taken as the indication that the evaporation of water from a free surface has been completed, i.e. the granular materials have reached a surface dry condition. In this respect it is not important to distinguish in a further drying process between a linearly decreasing drying rate and a subsequent non-linear drying process as controlled by the capillarity of the tested material. In the test, the drying may continue until a complete liberation of all pore water has been achieved.

In Figure 1, a schematic presentation of the drying rate of porous materials is given and the individual phases of drying are plotted against the water content of the porous material. In the proposed test method, drying is accelerated by an elevated ambient temperature. The diagram shows, that the drying rate increases during the heating phase (drying phase I), when constant temperature conditions have been achieved, a constant drying rate is expected until all surface water films have disappeared (drying phase II). Then, the drying rate decreases with time (drying phases III and IV) until a complete drying is achieved.

![Figure 1. Schematic presentation of the drying process of porous materials](image)

2. EXPERIMENTAL PROGRAMME

2.1 Test method and experimental set-up

In order to overcome the labour intensive stepwise drying and repeated testing of drying granular materials according to the standard test method [1], an automated test procedure was developed which basically consists of a continuous recording of the weight of the materials under investigation. A suitable weighing scale of sufficient accuracy is connected with a PC for continuous recording of the weight of the sample. The weight change due to drying is plotted against the drying time, thus giving a graphical representation of the drying rate. After complete drying has been achieved the amount of evaporable water is calculated as the total weight change, and the observed drying process is re-calculated to result in the actual drying rate at a given moisture concentration of the tested material. The plot of the drying rate versus water content then illustrates the individual drying phases and the transition from drying phase II to phases III/IV is identified as the saturated and surface dry condition (ssd). Further analytical processing of the recorded data also allows an automated identification of the transition from drying phase II to phases III/IV: By regression analysis of the drying rate the moisture concentration is calculated when the drying rate significantly deviates from a constant value.
The external drying conditions are controlled by a climate chamber, in which the materials under investigation are placed. In the climate chamber constant temperature conditions can be installed and controlled ventilation supports the removal of the evaporated water. The drying conditions are monitored continuously by recording temperature and relative humidity inside the drying chamber.

The tested granular material is placed on a flat sample container such that a large surface area and only a low height of the sample are kept. The sample container is attached to the weighing scale by a chain and the weighing scale itself is placed outside on top of the climate chamber. Figure 2 shows the principle of the test set-up.

In preliminary test runs the experimental recordings exhibited significant scatter and depending on the type of material as well as on the grain size distribution the transition between drying phase II and III/IV was not always sharp. Details of the experimental set-up as well as parameters of the drying conditions were then optimized to improve the stability of the recorded data. Important modifications were: The bottom of the sample container is permeable, e.g. a sieve or wire mesh. Depending on the grain size of the test material openings may vary, for fine sand openings as low as 0.063 mm may be used. Furthermore, the forced air flow inside the climate chamber must not directly hit the sample container, protecting shields were installed. For the accelerated drying a temperature of 65°C is recommended and the climate chamber is pre-heated before the test material is introduced. When the observed drying rate falls below a pre-set value, e.g. 0.02g/minute, the temperature of the climate chamber is increased to 105°C and drying is observed until a constant weight of the sample is achieved.

In the pilot tests, allows requirements on the minimum amount of test materials were established. The recommended sizes of samples are:

<table>
<thead>
<tr>
<th>Grains sizes</th>
<th>0.063 &lt; d &lt; 4 mm</th>
<th>250 grams</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4 &lt; d &lt; 8 mm</td>
<td>500 grams</td>
</tr>
<tr>
<td></td>
<td>8 &lt; d</td>
<td>1000 to 1500 grams</td>
</tr>
</tbody>
</table>
During drying phases I through IV data are recorded at intervals of 30 seconds, after the drying temperature is increased to 105°C data are recorded at time intervals of 15 minutes. Drying is completed when the observed weight change is less than 0.1% per hour. For most of the tested materials in the experimental study a test run was completed within 24 hours. Since the method is fully automated no continuous attendance by personnel is required.

2.2 Experimental programme

In an experimental programme the suitability and accuracy of the proposed test method was evaluated using the modified set-up and the drying parameters as described in chapter 2.1. Based on experiences with the standardized test method for the saturated surface dry density crushed concrete for recycled aggregates is most difficult to characterize, at the same time, this material represents the most important source for recycled concrete aggregates. Therefore, the main focus of the test programme was placed on crushed concrete and the grain size distribution and the band width of grain sizes in the test samples were varied. Further recycled materials such as crushed clay bricks or crushed calcium silicate bricks were tested as well, due to their pore structure, which controls the drying behaviour they are less critical to analyse.

In parallel to the experiments with the automated method for all test series the standardized method [1] was applied and the results observed for both methods were compared.

For both methods the preconditioning of the test materials consisted in the saturation with water according to the standardized method, i.e. ponding of the materials in water for 24 hours.

3. TEST RESULTS

In the following, results on the measurement of the moisture concentration at saturated surface dry condition are reported. As a result of the proposed test method the recorded drying curves are shown, from which the moisture concentration can be deduced at the transition point of drying at constant drying rate and decreasing drying rate. In the diagram, this value is denoted with SSD-AM. In addition to this value the corresponding result of the standard test is given in the diagram denoted with SSD-DIN. The individual diagrams also contain data on the grain size distribution of the crushed concrete and the mass of the tested sample.
Figure 3. Drying curve and values for SSD for crushed concrete, fraction 0/4 mm

Figure 4. Drying curve and values for SSD for crushed concrete, fraction 4/8 mm
crushed concrete, 8/16 mm
mass of sample: 1000 grams

Figure 5. Drying curve and values for SSD for crushed concrete, fraction 8/16 mm

crushed concrete, 16/32 mm
mass of sample: 1300 grams

Figure 6. Drying curve and values for SSD for crushed concrete, fraction 16/32 mm
Figure 7. Drying curve and values for SSD for crushed concrete, fraction 0/16 mm

The following Table 1 summarizes the results obtained.

Table 1. Water content of recycled crushed concrete in different grain sizes at saturated surface dry condition (SSD)

<table>
<thead>
<tr>
<th>Grain size distribution</th>
<th>Water content [% by mass] according to</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DIN EN 1097-6</td>
</tr>
<tr>
<td>0/4 mm</td>
<td>8,2</td>
</tr>
<tr>
<td>4/8 mm</td>
<td>5,4</td>
</tr>
<tr>
<td>8/16 mm</td>
<td>4,0</td>
</tr>
<tr>
<td>16/32 mm</td>
<td>3,3</td>
</tr>
<tr>
<td>0/16 mm</td>
<td>5,6</td>
</tr>
</tbody>
</table>

4. SUMMARY AND CONCLUSIONS

A new test for the determination of the density of porous granular materials was developed which comprises a fully automated measurement of the water content of the materials in the saturated but surface dry condition (SSD). Especially for fine grained materials with grain sizes less than 4 mm the water adsorbed to the external surfaces can achieve high values. The standardized test method for these materials is very labour intensive and subjective criteria are employed in the assessment of the water content.

In an experimental test programme on various granular materials, mostly crushed materials from construction and demolition waste (C&DW) which are frequently used as recycled aggregates for concrete production, the suitability and accuracy of the new test method were investigated. The results indicate that the method offers considerable advantages as compared to the standardized method, it is less labour intensive and the assessment of the water content at saturated but surface dry state is not based on subjective criteria.

The test method is based on the drying behaviour of porous materials, in the drying curve a transition from a constant drying rate to drying with decreasing rate is indicating the transition
from surface evaporation to a drying phase controlled by diffusion. This occurs after surface water has been liberated completely.

The method was applied to different grain size distributions of crushed concrete as a major source for recycled aggregates. The results achieved indicate that the new method can provide results on the water content in the saturated but surface dry condition, which are in good agreement with results obtained by the standardized method. A narrow band width of the grain sizes in the test sample allows a clear interpretation of the recorded drying curve, whereas a wider band width and a higher concentration of fines in the test material caused some uncertainty in the detection of the individual drying phases. Further results not reported here showed that similar problems may be encountered for mixed materials with significant differences in the individual drying processes.

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REFERENCES


