Abstract: In Portugal, ceramic tiles are frequently laid on facades. The temperatures of facades can easily reach 70 °C in summer, leading to fast drying and accelerated setting of the cementitious tile adhesive. These application conditions have a significant effect on the long-term secure bonding of tiling. The aim of the present investigation was to determine the critical factors for tiling under such harsh conditions, and explore ways to increase the durability of the tile work. Therefore, to study the impact of the formulation and application techniques on the tensile adhesion strength, different tile-adhesive formulations were applied, using different techniques, on concrete slabs stored under standard conditions and at 70 °C.

1. INTRODUCTION

In Portugal, ceramic tiles are frequently laid on facades. The temperature of these facades can reach 70°C or even higher when exposed to direct sunlight in summer. These high temperatures accelerate the drying of the cementitious tile adhesives (CTA). In practice, the tiling conditions are made even worse by wind. Such conditions are not favorable for secure fixing of the tiles.

In the present project, we set up a test program to investigate the different parameters that influence the adhesion of tiles. These parameters are:

- 4 different CTA formulations with different polymer contents, polymer to cement ratios (P/C), polymer types and water demands,
- different tile-laying techniques,
• different time delays before laying the tiles in the mortar bed,
• different pre-conditioning of the concrete slabs used as substrate,
• different climatic storage conditions of the tiled concrete slabs.

The test results clearly show the advantages and disadvantages of the described variations and modifications. Increasing the amounts of polymer binders improves the performance of the CTAs. Under the 70°C test conditions, the cement dries too fast. As a result, the polymer binder must support the full load in order to assure the bond to the tile. In addition, the buttering and floating technique helped to compensate for the accelerated drying conditions.

2. TEST PROGRAM
The test program consisted of tensile adhesion strength tests according to EN 1346 [1] and EN 1348 [2] on concrete slabs according to EN 1323 [3]. The concrete slabs were preconditioned for 7 d under standard conditions (sc) and for 7 d at 70 °C to compare the influence of the substrate temperature.
Four different CTA formulations with different polymer contents, polymer types, cement contents and water demands were chosen, and applied by different tiling techniques.
In order to determine the impact of the different parameters on the open time, the tiles were laid in the applied mortar bed immediately, and after 10 and 20 min delay.
For all tests, stoneware tiles according to EN 1348 (Winckelmans Blanc WB 5) were used. The detailed test conditions and parameter variations are given below.

2.1 Laying technique
In order to study the effect of different laying techniques, the tiles were laid in three variations:

• the classical thin-bed technique as described in EN 1348,
• the buttering technique (applying the CTA on the backside of the tile) and the
• buttering and floating technique (applying the CTA on the substrate and the backside of the tile).

For the classical thin-bed technique and the buttering and floating technique, the tiles were laid immediately, and after 10 and 20 min delay; for the buttering technique, the tiles were only laid immediately after the CTA had been applied to the tile.

2.2 Formulations and water demand
Four different CTA formulations were chosen:

• Formulation 1 is a flexible C2 ET-CTA
• Formulation 2 is a flexible C2 ET-CTA with high water demand
• Formulation 3 is a highly flexible C2 ET S2-CTA with low dosage of cellulosic ether
• Formulation 4 is a highly flexible C2 ET S2-CTA with low dosage of cellulosic ether

This choice was made to study how the tensile adhesion strength is influenced by the polymer amount and type, the cement amount and the water demand of the formulation.
The detailed formulations are given below:

**Formulation 1 (C2 ET):**

<table>
<thead>
<tr>
<th>Component</th>
<th>Part</th>
</tr>
</thead>
<tbody>
<tr>
<td>OPC White CEM I 52.5 R</td>
<td>400</td>
</tr>
<tr>
<td>Silica sand (0.63 mm – 0.71mm)</td>
<td>300</td>
</tr>
<tr>
<td>Silica sand (0.063 mm – 0.3mm)</td>
<td>200</td>
</tr>
<tr>
<td>Carbonate filler (0.2 mm)</td>
<td>46.5</td>
</tr>
<tr>
<td>Cellulose ether</td>
<td>3.5</td>
</tr>
<tr>
<td>Calcium formate</td>
<td>5</td>
</tr>
<tr>
<td>Polymer powder 1</td>
<td>45</td>
</tr>
<tr>
<td>Water demand [mL/1000g]</td>
<td>275</td>
</tr>
</tbody>
</table>

**Formulation 2 (C2 ET):**

<table>
<thead>
<tr>
<th>Component</th>
<th>Part</th>
</tr>
</thead>
<tbody>
<tr>
<td>OPC CEM I 52.5 R</td>
<td>500</td>
</tr>
<tr>
<td>Silica sand (0.63 mm – 0.71mm)</td>
<td>350</td>
</tr>
<tr>
<td>Silica microspheres</td>
<td>160</td>
</tr>
<tr>
<td>Cellulose fibers 0.2 mm</td>
<td>4</td>
</tr>
<tr>
<td>Diatomite</td>
<td>46</td>
</tr>
<tr>
<td>Microsilica</td>
<td>7.5</td>
</tr>
<tr>
<td>Cellulose ether</td>
<td>5</td>
</tr>
<tr>
<td>Calcium formate</td>
<td>10</td>
</tr>
<tr>
<td>Polymer powder 2</td>
<td>45</td>
</tr>
<tr>
<td>Water demand [mL/1000g]</td>
<td>515</td>
</tr>
</tbody>
</table>

**Formulation 3 (C2 ET S2):**

<table>
<thead>
<tr>
<th>Component</th>
<th>Part</th>
</tr>
</thead>
<tbody>
<tr>
<td>OPC CEM I 52.5 R</td>
<td>350</td>
</tr>
<tr>
<td>Silica sand (0.63 mm – 0.71mm)</td>
<td>300</td>
</tr>
<tr>
<td>Silica sand (0.063 mm – 0.3mm)</td>
<td>241.5</td>
</tr>
<tr>
<td>Cellulose ether</td>
<td>3.5</td>
</tr>
<tr>
<td>Calcium formate</td>
<td>5</td>
</tr>
<tr>
<td>Polymer powder 3</td>
<td>100</td>
</tr>
<tr>
<td>Water demand [mL/1000g]</td>
<td>230</td>
</tr>
</tbody>
</table>

**Formulation 4 (C2 ET S2):**
2.4 Polymer powder types
The polymer powders used in this study had the following chemical compositions:

- Polymer powder 1: vinyl acetate/ethylene/methyl methacrylate terpolymer, Tg = 12 °C
- Polymer powder 2: vinyl acetate/ethylene copolymer, with sag resistance, Tg = 18 °C
- Polymer powder 3: vinyl acetate/ethylene copolymer, Tg = 12 °C

All polymer powders are stabilized with polyvinyl alcohol as protective colloid.

2.5 Conditioning of the concrete slabs
For the purposes of this investigation, concrete slabs according to EN 1323 with the dimensions 40 cm x 40 cm x 3.5 cm were used. Some of the slabs were preconditioned for 7 d under sc, the others for 7 d at 70 °C in order to study the impact of temperature on the bonding strength of the CTAs.

2.6 Storage conditions of the tiled concrete slabs
The concrete slabs with the laid tiles were stored under 3 different conditions before the adhesion strength tests were conducted:

- 7 days under sc
- 4 days under sc followed by 3 days at 70 °C
- 7 days under sc followed by 21 days of water immersion

3. TEST RESULTS IN GRAPHIC REPRESENTATION

3.1 Results for Formulation 1

Concrete slabs stored for 7 d under sc:
Concrete slabs stored for 7 d at 70 °C:

### 3.2 Results for Formulation 2

Concrete slabs stored for 7 d under sc:

Concrete slabs stored for 7 d at 70 °C:
3.3 Results for Formulation 3

Concrete slabs stored for 7 d under sc:

![Graph for Formulation 3 with 10% Powder 3 - concrete slab sc]

Concrete slabs stored for 7 d at 70 °C:

![Graph for Formulation 3 with 10% Powder 3 - concrete slab 70°C]

3.4 Results for Formulation 4

Concrete slabs stored for 7 d under sc:

![Graph for Formulation 4 with 12% Powder 3 - concrete slab sc]
Concrete slabs stored for 7 d at 70 °C:

**4. DISCUSSION OF RESULTS**

**4.1 Influence of the temperature at tiling and time delay on laying the tiles**

The most critical factor for all adhesion tests turned out to be the high temperature of the substrate. When the tiles were laid on the hot concrete slabs, a significant drop of the bond strength could be observed for all formulations, application techniques and storage conditions. This effect was even more pronounced after 10 and 20 min delay before laying the tiles in the mortar, especially when the tiles were laid according to the standard thin-bed technique. In this case, the applied CTA lost most of its water by evaporation, the adhesion strength for all CTA formulations decreased to almost zero after 10 min.

When the tiles were laid using the buttering and floating technique, only the formulations with low polymer content experienced this time-dependent decrease. Both the C2 S2 formulations showed nearly constant values even after 20 min delay. Obviously, a higher Formulation 4 with 12 % Powder 3 - concrete slab 70°C

**4.2 Influence of technique and time delay of tile laying**

The development of the bond strength of the CTAs was independent of the tile laying technique, when the tiles were laid without time delay. After 10 and 20 min of waiting time, the buttering and floating technique showed clear advantages compared to the thin-bed technique. This can be explained by the fact that a skin forms on the surface of the applied CTA, which is only partly broken up when the tile is laid in the mortar bed.

In the case of the buttering and floating technique, the mortar is applied to the tile and substrate and the skin that forms on both surfaces is almost completely broken up when the wetted tile is laid in the mortar.

If the tiles were laid on the hot concrete slabs with a time delay of 10 or 20 min, hardly any improvement in adhesion was obtained by the standard thin-bed technique. By laying the tiles using the buttering and floating technique, a slight decrease of the bond strengths could be observed for the formulations with lower polymer contents, whereas the C2 S2 formulations stayed at a constant level even after 20 min delay.
polymer content in the formulation leads to longer open times and thus more secure bonding when tiles are laid on hot surfaces.

4.3 Influence of storage conditions
The highest values for adhesion strength were obtained after storage for 7 days under sc. The bond strength is significantly lowered, when the concrete slabs have been stored for 4 days under sc followed by 3 days at 70 °C. Here, cement hydration is stopped after 4 days by the heating of the slabs, leading to an evaporation of all the remaining water from the mortar.

The most critical conditioning step is storage for 7 d under sc followed by 21 d water immersion, which is in good correlation with all our previous CTA testing experience. This behavior can be explained by a swelling of the cementitious matrix caused by continued hydration of the cement particles during water immersion. The CTA therefore loses a lot of its cohesion and fails at lower pull-off forces. All the tested CTAs showed a cohesive failure pattern after water-immersion storage. If the CTAs had been allowed to redry before testing, the adhesion strength values would have recovered to, or even exceeded, the values that were obtained after storage under sc.

4.4 Influence of water demand
Formulation 2 with a very high water demand of 51.5 % showed no advantage in open time compared to the other formulations. The water in this formulation is apparently absorbed by the lightweight fillers and is not released to the surface of the applied mortar to avoid the drying of the surface. Also for the different storages, the additional water does not lead to a higher degree of hydration of the cement; the development of the bond strengths is of the same order as for formulation 1 having the same amount of polymer but less water demand.

4.5 Influence of cement and polymer content in the formulation
Considering only the cement content of the different formulations does not give a clear picture of the results. It is necessary to look at the polymer to cement ratio (P/C) for each formulation (P/C = 0.11 for formulation 1, P/C = 0.09 for formulation 2, P/C = 0.29 for formulation 3 and P/C = 0.4 for formulation 4), to get a better understanding of the results. An increase of the P/C leads to significantly higher bond strengths after all 3 storage conditions, especially when the concrete slabs were heated to 70 °C. If we look at the heated slabs, it is apparent that, with increasing P/C ratio, not only the adhesion strength, but also the open time, increases for all storage conditions when the buttering and floating technique is applied.

4.6 Influence of polymer type
The above results show that the temperature of the substrate, the laying technique, the storage conditions and the polymer to cement ratio in the CTA formulations are the most important parameters for bond strength development. As the formulations are very different, it is difficult to derive a clear impact of the polymer composition on the bond strength development.

4. CONCLUSION
With the test series of the present investigation, we attempted to determine in multiple dimensions the most important parameters influencing secure tile bonding to hot surfaces,
such as occur on facades exposed to direct sunlight. These parameters were identified via measurement of the bond strength of CTAs that were applied and stored under varying conditions. The bond strength was most strongly influenced by the temperature of the substrate in combination with the time delay between applying the mortar and laying the tiles in the mortar.

When the standard thin-bed technique was used, only immediate laying of the tiles led to good adhesion results. After a time delay of 10 min, almost no adhesion was detected. When the buttering and floating technique was used, the time delay of 10 and 20 min led to a decrease in bond strength development only for the formulations with the smaller amount of polymer powder. Both C2 S2 formulations with larger amounts of polymer gave values at a constant level.

To summarize, the use of high polymer-powder-modified CTA in combination with the buttering and floating technique led to a much more secure tiling work compared to the standard thin-bed technique, when the tiles are laid on hot surfaces.

A future investigation will examine whether the open time for the CTAs can be increased by the addition of more or different types of cellulosic ether.

5. REFERENCES