Microwave-induced interfacial failure to enable debonding of composite materials

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Abstract

Buildings or structures consist of materials that are joined to form functional composites to which a wide variety of "surface coatings" is added. Debonding of such composites is necessary to ensure high-quality, material-specific recycling processes. This paper describes tests of the debonding behavior of gypsum plaster and tiles that were attached to various types of concrete or wall materials such as brickwork, calcium silica blocks, or autoclaved aerated concrete. Selective heating with subsequent bond failure was achieved by exposing the interfacial layer of the materials to microwave-active substances. In all specimens subjected to this process, the finishing material was successfully separated from its base by microwave heating. No debonding was achieved in specimens without interfacial switching layer. Laboratory results were confirmed by tests performed using an in-plant demonstrator unit. In these tests, large fragments of gypsum plaster detached from the actual wall materials, which remained undamaged. Tiles also lost their adhesive bond to their base without damaging the latter.

Keywords: Debonding on demand, gypsum plaster, microwaves, susceptors, wall tiles.

Introduction

Buildings or structures are composed of materials that are joined together to form functional composites to which a wide variety of "surface coatings" is added. To ensure recycling and reuse, it would be desirable to apply appropriate methods to completely dismantle such combinated materials and to separate the single components from each other either during demolition or in the course of subsequent reprocessing at the recycling plant. This approach would create the basis for achieving material-specific recycling and reuse, including feeding back the material into the primary product.
Microwaves are electromagnetic oscillations ranging from 300 MHz to 300 GHz that can interact with materials in various ways. When a material is exposed to microwave radiation, it can absorb, reflect or transmit this radiation whilst a shift in the material's behavior may occur in line with the temperature increase. Highly dielectric materials absorb microwaves whilst their non-symmetrical molecules or free ions are caused to oscillate. The resulting friction leads to heating from the inside out. Materials with high electric conductivity, such as metals, reflect microwaves on their surface, consequently such materials do not heat up. Microwaves pass through transparent materials with no apparent effect.
In a research project jointly conducted by several institutions, the debonding of composites by microwave-induced interfacial failure was studied with a focus on two aspects:

- Disintegration of concrete by comminution along the aggregate-cement paste interfacial layers
- Debonding of multi-layer structural arrangements involving plaster or tiles attached to supporting materials

Parallel with the above tests to investigate the necessity of treating interfacial layers, the project partners also developed two “microwave ovens”, i.e. both a mobile and a stationary system that enabled treatment of the composite in-plant (at the recycling plant) and in-place (on the construction site). In the following sections of this paper, gypsum plaster attached to a load-bearing wall and tiles adhered to a variety of bases are used to describe the debonding process applied to multi-layer structural arrangements.

Experimental Set-up and Materials

Pertinent literature states that gypsum materials and tiles are microwave-transparent. So it is impossible that the finishing materials themselves react to the microwaves and are softened by the resulting heat development. Therefore microwave-active additives must be injected into or applied to the finishing materials to achieve the intended debonding effect. Various methods were developed for this purpose:

- Case 1: Gypsum plasters are modified with the addition of susceptors that act as microwave-active additives so that their bonding behavior is enhanced (Fig. 1a). This means that gypsum plaster can heat up by itself and undergo a chemical conversion process, which softens it and makes it easy to remove by mechanical processes.
- Case 2: Debonding occurs at an additionally introduced “interfacial switching layer” located between the gypsum plaster and its base (Fig. 1b). This interfacial switching layer must contain susceptors so that microwave absorption and heating occur exactly at the plaster-base interface. The resulting thermal stresses must exceed adhesive forces to ensure effective debonding.
- Case 3: Tiles provide three options for application: adding susceptors directly to the tile adhesive or applying additional interfacial switching layers either directly to the base, which may consist of various building materials, or to the back of the tile.

The tests presented in this paper concentrated on applying interfacial switching layers according to the arrangement shown in Figure 1 b and c.
Irrespective of the specific case, the characteristics of materials and composites must not undergo significant modifications. Materials that form the supporting structure or base layer should be heated to the smallest possible extent.

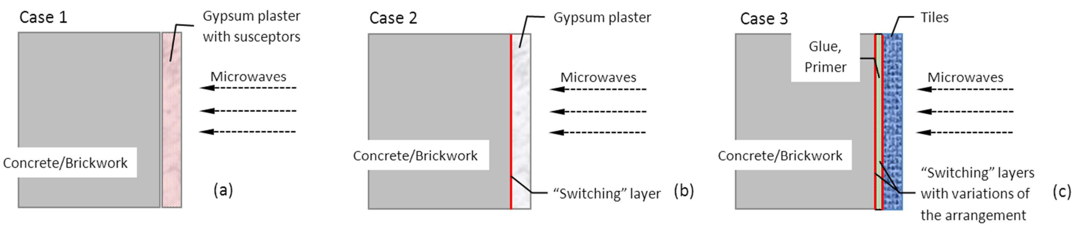

Fig. 1. Model for debonding multi-layer structures

To verify feasibility of the individual cases, a multi-stage program was devised to quantify the reactions of additives, commercially available mortars, plasters, and other solid construction materials and finishing materials to microwave radiation. The first step involved investigations of the microwave coupling behavior of different susceptors that were either taken from the literature or derived from own observations and that were potentially suitable as additives to gypsum plasters or for the interfacial switching layer. In the second step, tests on commercially available grout mortars and tile adhesives as well as various solid building

materials such as concrete, brickwork, minerally bound wall materials, natural stone etc. were performed. The results obtained from these tests were used to choose specimens from support materials to which gypsum plaster or tiles were applied. The contact surfaces between the materials were designed so that the debonding was expected.
The bonding behavior of investigated additives and building materials was assessed indirectly as a function of the surface temperature. For this purpose, identical test specimens with dimensions of 40 × 40 × 160 mm were produced and treated for 20 minutes during static storage in a laboratory microwave system with an output of 750 W. The microwave treatment followed the same procedure both with respect to the equipment and to process execution.
Specimens used for the investigations on susceptors consisted of calcium sulfate dihydrate, which is microwave-transparent. Prior to producing the prisms (with a water/gypsum ratio of 0.6), a certain amount of susceptors were added to the gypsum used to fabricate the dihydrate prisms. Prisms were stored at the laboratory until they reached equilibrium moisture. Specimens should be identical in terms of porosity and total water content. Variable parameters include the type and quantity of the susceptor whose influence has to be determined. Prisms produced from tile adhesives or building materials were dried to mass constancy prior to microwave treatment.
Debonding tests to separate multi-layer composites according to Case 2 (Fig. 1) were performed on slabs (150 mm × 150 mm × 40 mm) made of concrete, calcium silica brick, autoclaved aerated concrete, and brickwork. A susceptor-modified interfacial switching layer was applied to the surface and then covered with gypsum plaster. Moreover according to Case 3, the interfacial switching layer was directly applied either to the slab or to the tile. As additional variant, the tiles were applicated on a plasterboard. Commercially available tile adhesives were generally used.
An infrared camera, mounted outside the process chamber, was used to perform temperature measurements in a discontinuous pattern at 60-second increments in the first ten minutes and 120-second increments until the end of the treatment. Both maximum and mean surface temperatures were recorded during the entire process. Emission parameters of the building materials that were necessary to ensure accurate temperature measurements were taken from the literature [25].

Fig. 2: Test setup with gypsum specimen

Experimental observations

The comprehensive comparative tests carried out during the course of the project for the identification of suitable susceptors and the self-coupling behavior of different mineral building materials systems will not be discussed at this point.

Debonding of multi-layer structures

According to the above results, it is relatively easy to remove gypsum plaster from a supporting base if the plaster is modified by adding a susceptor, as shown in Case 1 in Fig. 1. Black graphite used as an additive leads to strong discoloration of the white plaster. However, it is questionable whether gypsum producers or end-users would tolerate grey to black gypsum plaster varieties.

The second option of debonding gypsum plaster from its base is to apply an interfacial switching layer, which acts as a predetermined breaking point under microwave exposure. This option does not change the color of the gypsum plaster. Successful debonding was demonstrated for all test specimens. Only minor amounts of up to 20% of gypsum plaster remained on the base and were debonded in a subsequent treatment step. Depending on the material, complete debonding required a mean treatment duration between 100 seconds for the gypsum-V brick specimen and 660 seconds for the gypsum-concrete specimen. Among other possible causes, these differences could be due to varying adhesive tensile strength parameters of the materials but also to the diverging patterns of absorption of irradiated energy exhibited by the materials themselves.

Fig. 4. Specimens with gypsum plaster prior to (top) and after (bottom) microwave treatment

Tile removal tests also demonstrated successful debonding in all cases, irrespective of the interfacial switching layer being located directly on the building material or on the tile. Complete and smooth separation was achieved, accompanied by an audible sound. The required mean treatment duration ranged from 62 to 76 seconds. Tiles could not be separated from the reference specimens without added susceptors.

Fig. 5. Specimens with tiles prior to (top) and after (bottom) microwave treatment

Supplement

First tests with an in-plant demonstrator unit were carried out. The tiles and the gypsum plaster were separated from the base material in all cases, if the interfacial switching layer was applicated.

Fig. 6. In-Plant demonstrator unit

Conclusions

Composite materials such as those used in contemporary buildings can make it difficult to recycle construction waste and demolition debris. Experimental tests were thus conceived to verify if and to what extent microwave treatment would be suitable for debonding such composites. Several varieties of gypsum plaster and tiles applied to concrete or wall materials were used for this purpose. An interfacial switching layer located between the supporting and finishing materials absorbs microwaves, which causes its temperature to increase.
Supplement
It was found that the separation cannot be realized by the temperature rise alone. In addition, an expansion must take place at the interfacial switching layer, which may be achieved by further additives.
A multi-stage test program found that certain types of graphite are well-suited to creating such a interfacial switching layer. These graphites were used in the plaster debonding tests. Plaster was added after their application to the wall surface. In the tile tests, the interfacial switching layer was applied either directly to the base or to the surface of the tile adhesive. In all specimens prepared, the finishing material was successfully debonded from its base in the course of microwave treatment. No debonding was achieved in specimens without added interfacial switching layer.
Laboratory results were consistently confirmed by tests performed on an in-plant demonstrator unit. Large fragments of gypsum plaster detached from the wall materials, which remained undamaged. Tiles also lost their adhesive bond to their base and were held in place merely by the pointing mortar. Supporting layers were not damaged.
Next research steps will concentrate on the development of additional interfacial switching interfacial layer designs as well as the installation of an in-place demonstrator unit suitable for use directly in buildings.

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