STUDY OF AN OPTIMIZED TILE MANUFACTURING PROCESS FROM THE GREEN CUTTING OF BIG CERAMIC SLABS

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ABSTRACT

In recent years, several forming technologies have progressively entered the market allowing manufacture of large ceramic slabs, with fired widths up to 1800 mm and variable lengths. Traditionally, the kitchen and bathroom furniture covering markets have been the targets of the products manufactured with this compacting technology. However, the versatility provided by the LAMGEA® technology, when combined with a

green cutting stage, allows it also to be used for also manufacturing ceramic tiles in medium to big sizes (600 mm x 600 mm, and higher).

The main disadvantage shown by the technology of tile manufacturing from green cutting of large slabs lies in the fact of generating a significant amount of discarded material in the cutting process. In this paper, the technical feasibility of recovering all the waste material originated in the green cutting operation in a ceramic tile forming line, based on LAMGEA® technology, has been studied. For this, the discarded material has been conditioned in a specially developed grinding system, obtaining a powder that has been reintroduced into the composition after mixing it with a certain proportion of "fresh" spray-dried powder. Specifically, the properties of products manufactured exclusively with spray-dried powder have been compared with the properties of products obtained using a mixture of spray-dried powder and 50% recovered material.

The results obtained in both the laboratory characterizations, as well as in tests performed under industrial conditions, demonstrate the technical feasibility of recovering, after a pre-conditioning process, the waste material resulting from the slab cutting operation.

1. INTRODUCTION

A typical LAMGEA® compaction line, configured for manufacturing ceramic tiles of medium/large size, starts with two dosing hoppers that deposit two overlapped layers of pressing powder on a polymeric conveying belt. The resulting powder bed, with a size slightly bigger than the final size of the green pressed product, is then conveyed by the belt to a hydraulic press (see figure 1).

The specially developed LAMGEA® press applies a uniaxial compaction strain (up to 400 kgf/cm^2, depending on the powder properties) on the powder by means of the vertical displacement of the metallic piston located in the lower part of the press. By slightly elevating the powder supported by the belt, it is forced to compact against the upper part of the press. On this upper part, pressing is not directly performed against the press but against another polymeric belt which is placed between the powder and the metallic structure of the press. The upper belt, which could show a flat or a structured surface, has up to four possible pressing positions, allowing definition of up to four different surface structures on the top of the green slabs. The position of the upper and the lower belts is controlled by means of a servo positioning system. In each pressing cycle the powder bed prepared by the dosing system is introduced into the press by the lower belt while the position of the upper belt is displaced. Once the powder is compacted, the non-pressed lateral margins are removed, and the resulting slab is carried by the lower conveying belt to a green cutting equipment.

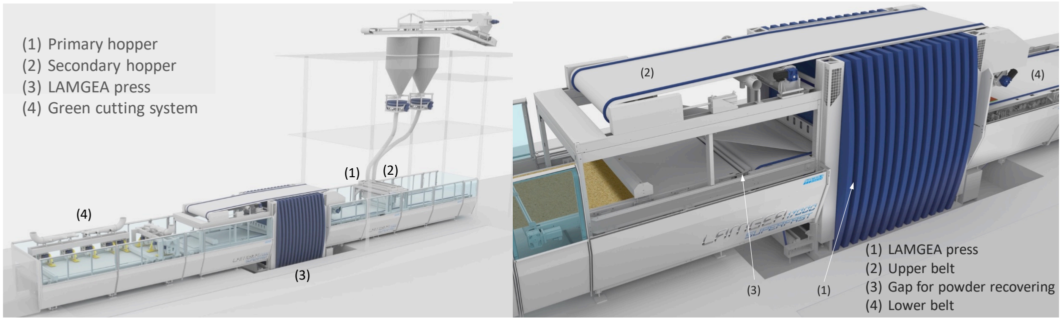

***Figure 1.** LAMGEA® shaping line (left) and details of the LAMGEA® press and conveying system (right).*

In the cutting stage, several diamond discs remove the front, back and lateral parts of the compacted slab to define a straight edge in the product. At the same time, if required, different sub sizes can be obtained by cutting the whole slab in smaller tiles. After the green cutting stage, the semi elaborated products are processed following a similar process than that followed in a conventional ceramic tile manufacturing line, i.e., drying, glazing and decorating (generally by means of full-digital lines), firing and sorting [1] [2].

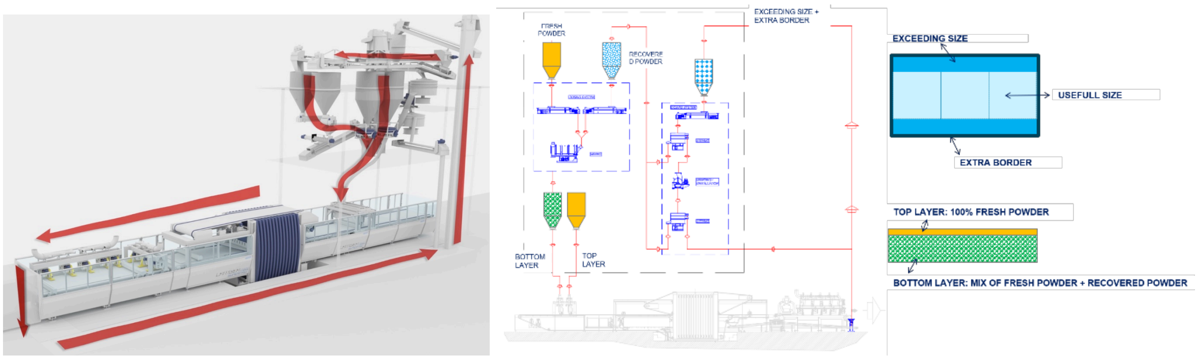

***Figure 2.** General powder flows in the developed scrap recovering system (left) and detail of the different powder layers constituting the product (right).*

System Ceramics is developing a recovery technology allowing reuse of the scrap generated during the pressing and the green cutting stages (see figure 2). This system mills and conditions the green scrap to reintroduce it into the powder composition to be pressed. The normal procedure to reintroduce the scrap after its conditioning consists of mixing it with a certain proportion (the necessary amount to always recover all the generated scrap) of fresh spray-dried powder. The resulting mix is then fed into the first hopper to make the bottom layer (rear side of tiles). The powder bed is completed by adding a thinner layer of fresh powder dosed by the second hopper (top side of tiles).

2. OBJECTIVE

The main objective of this study is to evaluate the impact of green scrap recovery on the properties of the products manufactured by means of the LAMGEA® technology. For this, an experimentation plan, both in laboratory and industrial conditions, was proposed to compare the properties of the semi-elaborated and final products obtained with the LAMGEA® technology and pressing powders of various typologies. Specifically, tests using two different powders were conducted. The references used for each powder were as follows:

- MIX: Mix of spray-dried powder with reused green scrap to obtain a double layer product. A first layer containing a mix of 50% green scrap and 50% spray-dried powder, and a second one only made up of spray-dried powder.
- STD: Fresh spray-dried powder without added green scrap.

3. EXPERIMENTAL PROCEDURE

The powder samples used for conducting the characterisation tests were directly collected from the conveying belts feeding a LAMGEA® industrial facility. At laboratory scale, the following properties of the compared powders were evaluated [3] [4] [5] [6] [7]:

- Granule size distribution.
- Powder flowability.
- Compaction diagram.
- Green mechanical strength.
- Dry mechanical strength.
- Loss on ignition.
- Thermal expansion and pyroplastic deformation.
- Vitrification diagram.
- Fired mechanical strength.

The industrial tests consisted of the comparison of the properties of the semi-elaborated and final products obtained in the facility with both powders' typology. In this case, the following tests were conducted [8] [9] [10] [11]

- Density and thickness distribution by mean of non-destructive X-ray inspection (on green and fired product).
- Dimensional characterisation of final product.
- Mechanical strength of the products (in dried and fired conditions).
- Water absorption of final product.

The industrial tests were conducted in a forming line which was shaping a single ceramic tile with sizes up to 1200 mm x 5400 mm after firing (1450 mm x 6050 mm, in the green state). The line was configured to later obtain six 900 mm x 900 mm fired tiles by green cutting from the complete tile. For each pressing powder, five complete tiles were shaped, at a maximum specific pressure of 400 kgf/cm^2, and conveyed to the green cutting equipment to obtain 6 fired tiles of 900 mm x 900 mm. The moisture content of the prepared tiles was later removed in a natural gas dryer. Some of the dried tiles were used to determine the green mechanical strength and the density, thickness and mass distribution of the products. The remaining tiles were fired in a natural gas single layer kiln at a maximum firing temperature of 1205ºC, to complete the characterization.

4. RESULTS AND DISCUSSION

Figure 3 shows the granule size distribution of the two tested materials as well as the distribution corresponding to the recovered material, SCRAP, previously to be mixed with STD spray-dried powder. Pronounced differences are observed between the materials in the fraction with sizes higher than 710 µm. With regard to the thinner fractions, the MIX composition contains a higher fraction of sizes below 125 µm than the spray-dried powder

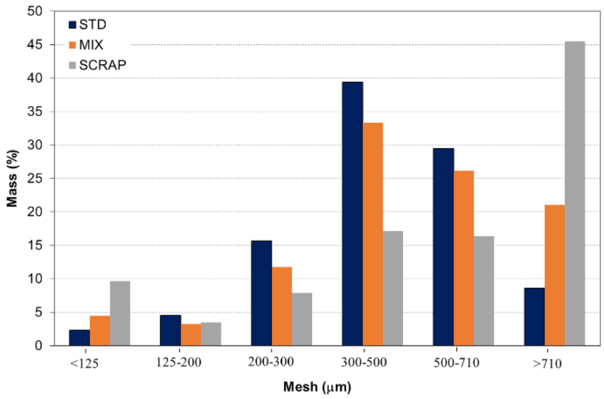

Figure 3. *Granule size distribution.*

Figure **4** to figure 6 show the morphology of this fraction and the fractions 710-500 µm and <125 µm. These images show that the coarser material from the green cutting scrap is concentrated mainly in the fraction of sizes higher than 710 µm, being made up of irregular agglomerates bigger than those shown by the spray-dried powder. The fraction 710-500 µm has a similar morphology for both materials. From these results it can be concluded that the material obtained from the green cutting scrap recovery is characterized by the presence of big irregular agglomerates and fine powder.

Figure 4. *Micrographs of the samples <125µm. STD (left), MIX (centre) and SCRAP (right).*

Figure 5. *Micrographs of the samples 500-710 µm. STD (left), MIX (centre) and SCRAP (right).*

Figure 6. *Micrographs of the samples >710µm. STD (left), MIX (centre) and SCRAP (right).*

The flowability of the MIX material, measured as mass flow rate, is slightly lower than that corresponding to the STD powder (table 1). This can be explained by the previous results, as the presence of powder in the smaller fraction (<125 µm) usually lowers flowability, this decrease being partially compensated by the big agglomerates.

Composition	Flowability (g/s)
STD	27,9
MIX	23,8
SCRAP	19,2

Table 1. *Flowability of the tested materials.*

In any event, the observed difference is small enough to guarantee good behaviour of the MIX material when flowing from the dosing hoppers. The flowability of the SCRAP material is lower than that of the STD and MIX compositions, because of the big presence of fine particles in the material. Using SCRAP without mixing does not guarantee good flow behaviour of the material, which has been also evidenced during the laboratory tests, as interruptions in the discharge flow were observed when performing the flowability characterisation.

For the determination of pressing behaviour, the moisture content of both materials was determined (table 2). As the observed differences could alter the pressed specimen properties and their firing behaviour, the MIX composition was conditioned to the same moisture content than STD composition (6,2 wt%) for all the tests. In this way, the differences which could be observed between the two materials could be exclusively attributed to green scrap recovery.

Composition	STD	MIX
Moisture content (wt%)	6,2	5,8

Table 2. *Moisture content (dry basis) of the tested materials.*

Moisture content (%)	Pressure (kg/cm^2)	Bulk density STD (kg/m^3)	Bulk density MIX (kg/m^3)
6,2	250	1865	1881
6,2	350	1909	1921
6,2	500	1958	1966

Table 3. *Compaction diagram of the tested materials (bulk density on a dry basis).*

Table **3** and figure 7 show the compaction diagram of the tested materials at the same moisture content of 6,2 wt%. The compaction diagrams reveal a slightly higher bulk density of MIX powder with respect to STD powder, when pressing them at the same pressure and moisture content. This behaviour is typically caused by the presence of dense agglomerates such as those observed in the fraction >710 µm of MIX powder, especially if they are accompanied by small granules and powder. In fact, the wider granule size distribution, shown by the MIX material, leads to a better particle packing during pressing and thus to slightly higher densities than those obtained with the STD material. As the tiles obtained in the industrial trials had a bulk density of approximately 1950 kg/m^3, the characterization of the pressed specimens at laboratory scale was performed applying the maximum pressing pressure required to obtain this bulk density (table 4).

Due to the higher compaction degree attained with the MIX powder, the pressing pressure required to obtain the same bulk density was slightly lower. In these conditions, the mechanical strength of both the green specimens and the dried specimens was lower for the MIX composition than for the STD composition. It may be noted that all the values are acceptable, and the differences are not high.

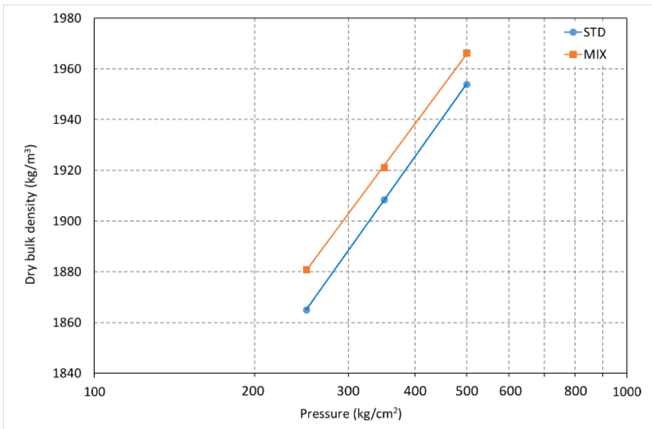

Figure 7. *Evolution of dry bulk density with pressing pressure.*

To complete the characterization of pressing behaviour, the surface of the industrially pressed tiles was observed with a stereoscopic microscope equipped with a camera. It must be considered that at industrial scale the tile with MIX powder had an upper layer (around 18% of the whole thickness) of spray-dried powder without recovered material. The topography, which is shown in

, is very similar for the two pieces, the structure observed being associated with the upper belt used on the industrial facility

Figure 8. *Surface micrography of the pressed tiles MIX (above) and STD (below).*

Composition	STD	MIX
Moisture content (%)	6,2	6,2
Pressure (kg/cm^2)	495	450
Bulk density (kg/m^3)	1955	1955
Green mechanical strength (N/mm^2)	1,2	1,0
Dry mechanical strength (N/mm^2)	3,3	2,9

Table 4. *Summary of the physical properties of the evaluated compositions.Ç*

The dimensional changes of the tested materials are plotted in figure 9. The figure shows a significant coincidence of both the magnitude of the final shrinkage (around 6,7%) and the shape of the curve. Vitrification diagrams of the two powders are displayed below. These results show, as was expected according to the dilatometric analysis, very similar behaviour during the firing stage for both studied materials. At laboratory scale, maximum densification temperature was 1175ºC for the two materials.

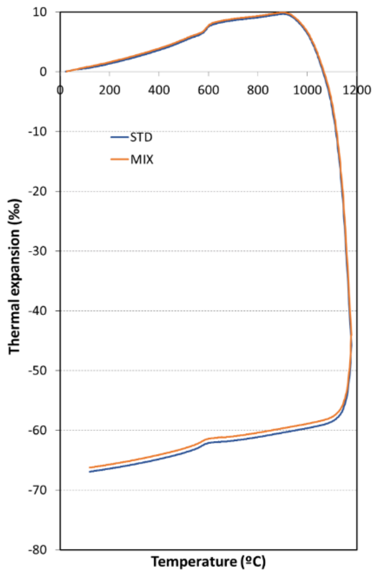

Figure 9. *Expansion-shrinkage curves for both tested materials.*

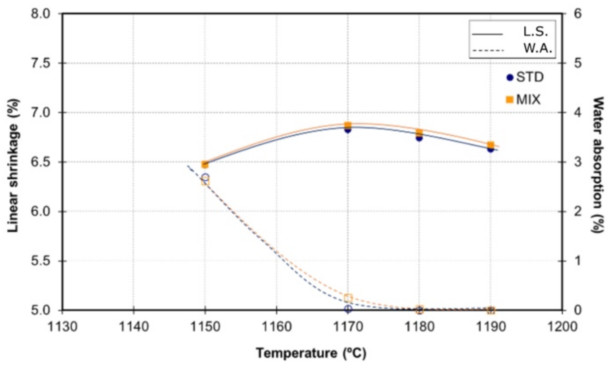

Figure 10. *Linear shrinkage (L.S.) and water absorption (W.A.) with temperature. Vitrification diagram.*

Figure 10 shows the linear shrinkage and water absorption at different maximum firing temperature, the main differences being the slightly higher water absorption of the specimens obtained with MIX powder (which are still below the limit required for tiles of Group BIa, lower than 0,1% for both materials) and the reduction of around 10% in fired mechanical strength. These small differences can again be attributed to the presence of coarse dense agglomerates in MIX powder, but they have no special significance.

Deformation during the firing stage (figure 11) was measured with the optical fleximeter, providing, as expected, similar behaviour for the two pieces. In this case, in order to reproduce industrial trial conditions, the specimen with MIX powder had an upper layer (around 18% of the whole thickness) of spray-dried powder without recovered material. It can be observed that the curvature is directly related to the pyroplastic deformation.

Composition	STD	MIX
Temperature (ºC)	1180	1180
Bulk density (kg/m^3)	2351	2347
Linear shrinkage (%)	6,7	6,7
Water absorption (%)	<0,1	<0,1
Loss on ignition (%)	3,22	3,28
Mechanical strength (N/mm^2) *	64	57

** To meet standard (UNE EN ISO 10545-4: 2015) R>35 N/mm^2*

Table 5. *Properties at maximum densification.*

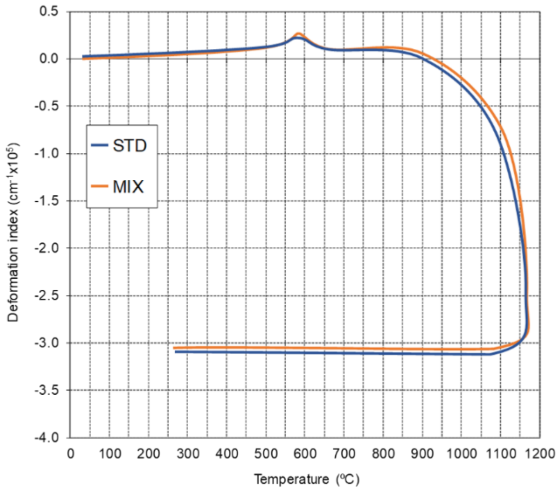

Figure 11. *Deformation curves obtained for both materials.*

Because of the increase in the quantity of glassy phase and the reduction in viscosity of this phase when temperature rises, the deformation index increases with firing temperature. For both materials, the observed behaviour was very similar.

The density and thickness distributions were determined by X-ray inspection of 6 green tiles obtained from the same slab at the industrial plant. The tiles were tested individually according to the position of each tile in the pressed slab. Thus, the behaviour of both materials during pressing of big slabs can be compared. Each studied property is shown in the resulting maps by means of a colour scale. On the one hand, the higher values of the concerning property are represented by warm colours and, on the other, cold colours represent the lower property values. The results of the fired tiles are shown in figure 12 and figure 13. No significant differences are found between the properties of the tiles shaped with the mix composition and the ones obtained from the STD material. The heterogeneities detected are very similar from one slab to the other, which could only be explained by the fact they are not related to powder behaviour but to the regulation of the processing equipment.

The global average green density for the MIX composition was 1946 kg/m^3, while for the STD material, a 1948 kg/m^3 density was obtained. Concerning the thickness of the samples, the ones obtained with the MIX material were slightly thicker than the tiles shaped with the STD composition. This could be related to the different compaction development observed when the behaviour of the powders has been studied at a lab scale. In fact, the laboratory tests have shown a better compaction of the MIX composition, which would be related to the higher thickness of the MIX trial samples, for the same dry bulk density. A wider granule size distribution in the MIX material would origin a better particle packing, and a higher quantity of powder deposited on the belt for the same height of the dosing leveller.

The characterisation of the dried industrial tiles was completed with the determination of the mechanical strength. These tests have shown a slight difference of just 3% between the mechanical strength of both compositions. The tested MIX tiles had a mechanical strength of 3,3 N/mm^2, while the STD showed a value of 3,4 N/mm^2. This difference is not big enough to justify a significant difference in the behaviour of the materials during their handling up to the firing process.

Composition	STD	MIX
Bulk density (kg/m^3)	1948	1946
Thickness (mm)	10,03	10,35
Mechanical Strength (N/mm^2)	3,4	3,3

Table 6. *Physical properties of the dry tiles collected during the industrial tests.*

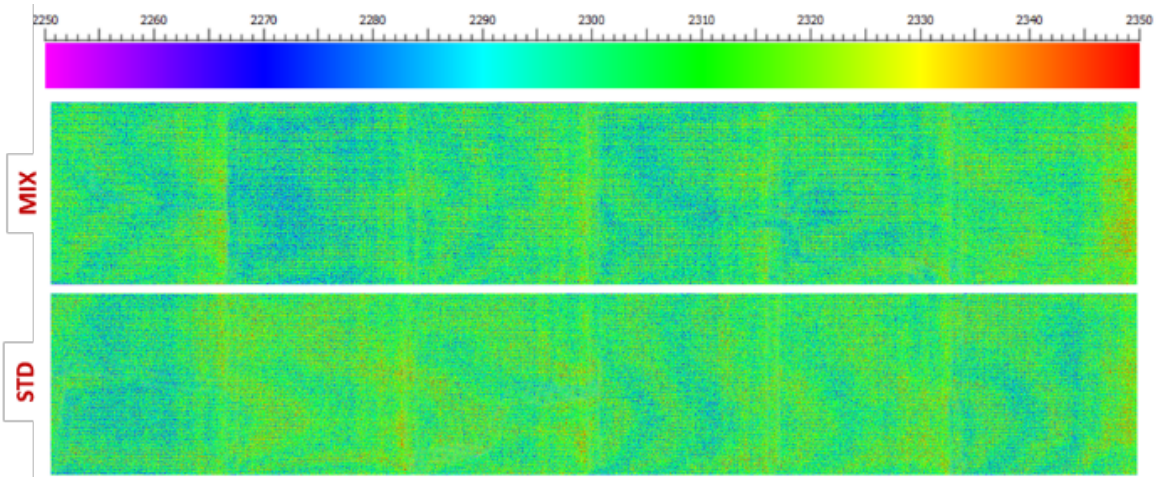

Figure 12. *Fired density (kg/m^3) distribution of six 900 mm x 900 mm tiles obtained from green cutting of a big slab.*

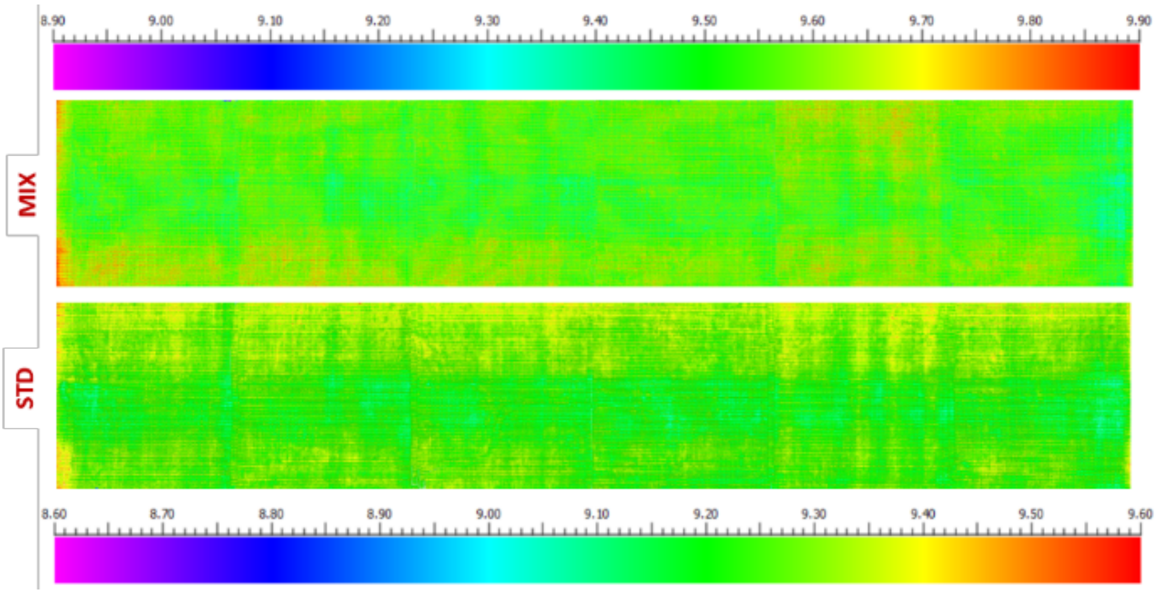

Figure 13. *Thickness (mm) distribution of six fired 900 mm x 900 mm tiles obtained from green cutting of a big slab.*

The dimensional characterisation of the fired tiles demonstrates very similar behaviour of both materials during the firing process. As can be seen in table 7, the average side length obtained in both cases is very similar, with just 0,2 mm difference between them and an analogous maximum deviation of the length. Average side size, for the same firing conditions, is directly related to the average bulk density of the dry tiles. If some differences in the compaction behaviour of the materials had been experienced, the dimensions obtained in these tests would have shown higher differences.

In regard to the lack of orthogonality of the product, the observed deviations are quite comparable in both cases, with a maximum straightness of the sides of -1,9 mm for the two kinds of tiles evaluated. The deviations in the orthogonality of the tiles are directly related to the density distribution inside every tile before firing. Obtaining the same deviations means that the powder distribution during powder dosing is not affected by the nature of the pressing powder. This result reinforces the results determined by the laboratory tests.

Similar results were found in the curvature of the fired tiles. A non-significant difference between the curvatures of the tiles was detected, the maximum central curvature in both cases being around -1,0 mm. This result is in accordance with the laboratory dilatometry which has shown an almost identical expansion-shrinkage curve for both materials. Thus, when pressing in the case of the MIX powder, by putting a second layer of spray-dryer powder on the top, there is a good coupling between the layers involved, not contributing to a modification of final product curvature.

Finally, the main properties of the final product, i.e. water absorption and mechanical strength, do not depend on the pressing powder used to shape de tiles. For both compositions, a 0,3% water absorption was obtained and just a difference of 4% in the modulus of rupture was observed. The water absorption obtained in the industrial tests is slightly higher than the one obtained in laboratory conditions because the industrial firing temperature (1205ºC) was higher than the optimal maximum densification temperature (1175ºC). Consequently, the industrial tiles showed lower bulk density than the laboratory samples, which is also related to their lower mechanical strength in comparison with the laboratory results.

Composition	STD	MIX
Fired average density (kg/m³)	2305	2302
Thickness (mm)	9,30	9,56
Average side length (mm)	906,3	906,5
Maximum deviation of the length (%)	-0,04 / 0,04	-0,07 / 0,04
Straightness of the sides (mm)*	0,6 / 0,9 / -1,8 / -1,9	0,6 / 0,8 / -1,5 / -1,9
Central curvature (mm)**	0,1 / -1,3	0,1 / -1,0
Water absorption (%)	0,3	0,3
Fired mechanical strength (N/mm²)***	47	45

**Maximum deviation from the straightness for each side*
***Minimum and maximum value for the central curvature on all the collected samples*
****To meet standard (UNE EN ISO 10545-4: 2015) R > 35 N/mm2*
Table 7. *Physical properties of the fired tiles collected during the industrial tests.*

5. CONCLUSIONS AND REMARKS

The conclusions derived from this study are as follows:

- It is possible to work with a high amount of recovered green scrap material (up to 50% of recovery has been evaluated in this work) for shaping ceramic tiles with a LAMGEA® manufacturing line. The properties of the final products obtained with a composition including green scrap, from the green cutting stage, are very similar to those of tiles produced with a conventional spray-dried composition.
- The tests conducted at a laboratory scale on both compared compositions show a similar pressing behaviour between them. Just slightly differences have been observed on the compaction degree attained during pressing, not significantly affecting the physical properties of the dried semi elaborated products.
- The evaluation of firing behaviour at laboratory scale reveals a similar development of the vitrification reactions in both materials. The physical properties of the fired products are the same in every case. No differences in the dilatometric and deformation curves are observed.
- The tests conducted at industrial scale evidence a similar processing behaviour of both materials. The physical properties of the semi elaborated dried samples collected during the tests are almost identical. This is translated into similar behaviour of the products during industrial firing and in the final products, which display the same water absorption, dimensional stability and mechanical strength.

The industrial tests conducted show the technical and competitive advantages of the LAMGEA® technology in a relevant operational context. The green scrap recovery system evaluated in this work is especially interesting for achieving high process flexibility as the size of the shaped tiles can be changed digitally by means of software settings without requiring any mechanical intervention. In addition, the operational costs are reduced since the system allows the reintroduction into the composition of the scrap generated during manufacturing with a significant environmental impact reduction.

6. REFERENCES

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