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1 **Crust formation and its role during bread baking**

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8 **ABSTRACT**

9 The final properties of the crumb and crust differ according to their heat-
10 moisture dynamics. Compilations of heating and drying rates reported in
11 the literature are discussed and will serve to validate future models of
12 baking. Their impact on the structural elements in dough films and the
13 porous network are discussed, highlighting the lack of data and the need to
14 reproduce these dynamics inside the instrument of analysis. Some roles of
15 the crust setting during the whole baking process are also presented,
16 suggesting further research in this area. Finally, as the region covered by
17 the crust should be defined as a starting point to future studies, definitions
18 proposed in the literature are discussed.

19 **Keywords**

20 crust, bread, baking, water loss, temperature, heating rate, heat and mass
21 transfer, mathematical model, porosity, permeability, rheology, starch
22 gelatinization, oven-rise, density, bubble, cell, CO₂ release, pressure

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1 **1 Introduction**

2 During baking, heat (HT) and moisture (MT) transport take place in the
3 dough simultaneously and interdependently, and involve three major
4 changes – (for further details see recent review by Mondal & Datta (2007)):

5 (1) Water vaporises at the cell/dough interface, and gases accumulated
6 during fermentation (CO₂, ethanol) or generated by chemical raising agents
7 are also vaporised: the cell volume increases provided that the dough film
8 retains gases and is deformable.

9 (2) Starch gelatinisation and protein coagulation transform the viscous
10 dough into a mainly elastic crumb; these rheological changes limit the cell
11 growth described in (1) and enhance pressure build-up.

12 (3) The structure with gas cells separated by films is transformed into a
13 porous structure with inter-connected pores. In theory ruptured films limit
14 cell growth (1): gas molecules are exchanged between adjacent open cells,
15 and finally transported out of the dough. Dough films rupture when they
16 can no longer withstand over pressure. Film rupture is often associated with
17 the onset temperature of starch gelatinisation (Bloksma, 1990) or a higher
18 temperature. This is also likely to happen if pressure is low, but the dough
19 film presents poor mechanical resistance, as when the protein content in the
20 flour is low, the water content in dough is high, or if the dough is under or
21 over-kneaded (Dobraszczyk & Salmanowicz, 2008).

22 The crust and crumb come from the same original dough, but their final
23 properties differ according to a distinct local heat-moisture treatment. As
24 soon as the dough is placed in the oven, water evaporates very fast from the
25 surface layers, resulting in a much lower water content (< 20% wet basis)

1 than at the core. The total water loss (WL) from the crust is obviously of
2 economic significance (weight loss). Water distribution between the crust
3 and crumb also contributes substantially to the organoleptic perception of
4 the final product. As the water activity (A_w) of sponge cake increased from
5 ~ 0 to 0.75, both initial modulus and critical stress fell by an order of
6 magnitude with both correlating ($r > 0.90$) with a trained panel's assessment
7 of sensory harshness (Attenburrow, Goodband, Taylor & Lillford, 1989). A
8 crispy texture is also associated with low moisture content and water
9 activity, when starch and gluten matrix are in a glassy state making cells
10 walls more prone to fracture (Stokes & Donald, 2000). Low water content
11 in the crust will also affect the rheological changes in the dough films and
12 ultimately the cell growth during baking. Starch gelatinisation and protein
13 denaturation are limited when there is restricted access to water. This has
14 an effect antagonistic to the one of the decreasing water content and may
15 prolong the deformability of dough films. The enhanced escape of gases
16 due to the proximity of the boundary to the oven may explain the smaller-
17 sized cells which are typical of the crust. These obviously contribute to the
18 mechanical properties of the crust (resistance to rupture during baking,
19 texture in mouth) in addition to the low water content.

20 As the water content decreases in the crust, the temperature can exceed
21 100°C , which supports other reactions such as the Maillard reaction
22 responsible for the development of colour and the release of flavours, and
23 also the production of toxic compounds with safety implications (Ahrne,
24 Andersson, Floberg, Rosen & Lingnert, 2007).

1 Reactions specific to the crust also jeopardize the nutritional value of the
2 baking process. On the one hand, the Maillard reaction decreases the
3 protein digestibility and the lysine bioavailability of lysine which is the
4 limiting amino-acid in cereal products (O'Brien & Morrissey, 1989). On the
5 other hand, gelatinised starch can be degraded by amylases from the saliva
6 whereas ungelatinised fraction undergoes a much slower metabolism and
7 can remain undigested. Conversely, health benefits (obesity risk reduction)
8 are claimed since bread rolls with a higher proportion of crust have been
9 reported to raise capillary blood glucose more slowly than a corresponding
10 loaf (Glatzel & Rettenmaier, 1962).

11 All these microstructural changes in the cell size and dough films also
12 contribute to the structural differentiation of the crust. Most previous
13 studies have focused on the crust properties at the end of baking or their
14 changes during storage (Luyten, Pluter & van Vliet, 2004), but the setting
15 of these properties during the baking and post-chilling processes have been
16 little studied to date.

17 The first aim of this review is therefore to present how the well known final
18 properties (once cooled) are created dynamically during baking and how
19 the underlying transformations differ from those in the crumb (section 2).

20 The crust properties differ from a bread making technology to another (pan
21 bread versus hearth bread for instance), but also from one face to the other,
22 depending on the extent of heat and mass transfer at the bottom and top
23 surfaces for instance. Given the very few data available in the literature on
24 the topic, elaborating a typology from this review is out of scope; however,

1 the variety present in the literature will help to identify key factors in the
2 crust setting process.

3 Improvements in the observation techniques will be highlighted in section 2
4 and summed up in the conclusion.

5 As the crust cannot be considered separately from the rest of the bread, but
6 interacts with other mechanisms, some of its role during baking already
7 identified in the literature will be presented in section 3.

8 As changes in bread are gradual, proposing a simple definition of the crust
9 is a difficult although necessary starting point for future studies, a second
10 focus of the concluding section (4).

11

12 **2 Mechanisms specific to the bread surface and contributions to** 13 **crust formation**

14 **2.1 Temperature**

15 Surface temperature quickly reaches 100°C and then approaches more
16 slowly the oven air temperature. This rapid increase in surface temperature
17 is enhanced i) by the low thermal conductivity of the aerated dough limits
18 HT at core; ii) by high radiation originating from the warm oven walls
19 (from 66.2 to 81.5% of overall HT) (Baik, Marcotte & Castaigne, 2000).

20 Surface temperatures exceeding 100°C are explained by the difference in
21 water content between surface and core: water evaporates from the surfaces
22 more quickly than it can be transported from the core; in addition, due to
23 the evaporation-condensation-diffusion mechanism (Wagner, Lucas, Le
24 Ray & Trystram, 2007), water content remains almost constant at the core.

25

1 Table 1 summarizes the heating rates observed at the surface compared to
2 the centre, as approximated by the slope of the linear segment between the
3 initial temperature and 100°C. The heating rate was high in the crust (up to
4 14.4°C/min) while not exceeding 3°C/min at core. Note that time derivation
5 of temperature kinetics gave even higher values (20 to 35°C/min) at the
6 onset of baking.

7 Temperature was measured using thermocouples (Zanoni & Peri, 1993;
8 Dogan, 2002; Lostie, Peczalski, Andrieu & Laurent, 2002a) or optic fibres
9 (Wagner, Loubat, Sommier, Le Ray, Collewet, Broyart *et al.*, 2008b)
10 placed at different locations inside the loaf, usually only near the top
11 surface and in the centre. However, this intrusive technique introduces
12 biases, including delicate positioning (1-3mm of accuracy), possible heat
13 conduction along the metallic wire of the thermocouple and constraint to
14 oven-rise. To minimize such bias, surface temperature can be monitored by
15 infra-red sensors (Lostie, Peczalski, Andrieu & Laurent, 2002b; Primo-
16 Martin, van Nieuwenhuijzen, Hamer & van Vliet, 2007).

17 **2.2 Water content**

18 The water content in the crumb remains almost constant compared to the
19 initial value while considerable dehydration occurs in the crust (
20 Figure 1). Water activity can also be used to describe the result of WL and
21 its effects on water availability, reaction kinetics and mechanical properties
22 (Czuchajowska, Pomeranz & Jeffers, 1989; Lind & Rask, 1991; Bassal,
23 Vasseur & Lebert, 1993; Dogan, 2002; Van Nieuwenhuijzen, Tromp,
24 Hamer & Van Vliet, 2007). Given the low final water content in the crust (

1 Figure 1), a moderate variation in water content can affect A_w considerably
2 (Lind *et al.*, 1991). A_w is also involved in the calculation of water transfer
3 during baking, since the driving force was generally assumed to be the
4 difference in partial vapour pressure between the product surface and the
5 oven atmosphere. A_w was measured at ambient temperatures, and very
6 little information is available for temperatures observed in the crust during
7 baking. Studies have been carried out at 100-150°C for cake dough (Bassal
8 *et al.*, 1993), and at 80-120°C for wet and dried crumb (Jury, Monteau,
9 Comiti & Le-Bail, 2007). Additionally, the assumption of thermodynamic
10 equilibrium between liquid and gaseous phases on which the measurement
11 of A_w is based have also been questioned, given the high heating rates
12 involved during baking (Zhang & Datta, 2006). This approach was
13 therefore not included in this review.

14 HT has been considered the main driving force for water vaporisation; in
15 other words, MT from the vaporisation front to the loaf outside, proceeding
16 mainly by convection, was not considered to be a limiting factor (Lostie,
17 Peczalski & Andrieu, 2004; Zhang, Doursat, Flick & Lucas, 2008). HT can
18 be enhanced by increasing the oven air temperature, and eventually the air
19 renewal at the product surface; these variables have consistently been
20 experimentally correlated to WL (Wahlby & Skjoldebrand, 2002). The
21 addition of steam increased the relative humidity of the oven air to 0.7-0.9
22 (Wiggins, 1998). As the dough surface was cold compared to the
23 surrounding air, moisture condensed onto it from the air, up to 1% of loaf
24 weight. Steam injection thus reduced WL at the onset of baking. However,
25 as the surface reached the dew point temperature, steam accelerated

1 temperature rise and WL for long baking times (Eliasson & Larsson, 1993).
2 Chevallier, Della Valle, Colonna, Broyart & Trystram (2002) reported
3 greater WL with higher air humidity in the oven (20 to 400 g/kg of dry air)
4 for biscuits. Internal resistance to HT also affects WL; because this
5 involves interlinked mechanisms, it will be discussed in section 3.

6 Water content was generally obtained by weighing the product after
7 stopping the baking process at different times, which is extremely time
8 consuming. Moreover, assessing profiles requires cutting the loaf into
9 samples while still hot, and also deformable. Vaporisation of water from
10 cut surfaces and squeezing crumb samples are thus sources of bias. Another
11 difficulty of the sampling method was separating the crust from the crumb.

12 Thorvaldsson & Skjöldebrand (1996) developed an infrared method for
13 continuous measurement of local water content, but the effect of crumb
14 density on the infrared signal was not corrected, generating bias during the
15 oven rise period.

16 Validating the thorough description of the mechanisms of water transport
17 (Zanoni *et al.*, 1993; Lostie *et al.*, 2002a; Lucas, Wagner, Doursat, Flick &
18 Trystram, 2009) would obviously require higher spatial and temporal
19 resolution for profiles of water content; this difficulty has been
20 demonstrated for the crumb (Lucas *et al.*, 2009) and is valid for the crust
21 with even greater acquisition constraints (spatial domain of a few hundred
22 to a few thousand μm). Note that experimental evidence hardly supports a
23 modelling approach based on uniform temperature and water content as
24 suggested by (Fan, Mitchell & Blanshard, 1999).

1 **2.3 Biochemical reactions**

2 2.3.1 Starch gelatinisation

3 The degree of starch gelatinisation (DSG) can be observed on final cereal
4 products (once completely cooled) by the loss of birefringence of starch
5 granules or the disappearance of the "Maltese crosses" observed in
6 polarized light (Eliasson *et al.*, 1993; Jenkins & Donald, 1998). DSG has
7 been shown to be directly affected by water (Burt & Russell, 1983; Le
8 Meste, Huang, Panama, Anderson & Lentz, 1992; Jenkins *et al.*, 1998;
9 Fessas & Schiraldi, 2000; Cuq, Abecassis & Guilbert, 2003) and the
10 heating rate (Donovan, 1979; Bloksma, 1980), which again both differ
11 between the crust and crumb. If DSG consistently differed between cereal
12 products because of their different compositions and baking times (Eliasson
13 *et al.*, 1993), it also varied within the same product: the greater the distance
14 to the surface, the greater the starch gelatinisation (Luyten *et al.*, 2004). Up
15 to 40% of the starch in the crust did not gelatinize during bread baking
16 (Primo-Martin *et al.*, 2007). This was consistent with DSC measurements
17 carried out with open pans (Fessas *et al.*, 2000): for a global water content
18 decreasing from 44.2 to 30.7% (wb), DSG was about 44% -instead of 66%
19 measured for sealed pans at initial water content of 44.2%.

20 Heat-moisture treatment of starch is known to affect the gelatinisation
21 temperature. Differential scanning calorimeter (DSC) thermograms
22 obtained from samples of high water content (>90% wet basis (wb))
23 exhibited a single endotherm peak (
24 Figure 2). Beyond this point and at water contents above ~60%wb, the
25 endotherm presented three major endotherms (Eliasson, 1980; Burt *et al.*,

1 1983; Champenois, Colonna, Buléon, Valle & Renault, 1995), the first
2 peak corresponding to cooperative, water-mediated melting of starch
3 crystallites, the second peak to the melting of the remaining crystallites, and
4 the third to amylose-lipid complex melting transition (Biliaderis, Maurice
5 & Vose, 1980; Burt *et al.*, 1983; Chevallier, Colonna & Lourdin, 2000;
6 Fessas *et al.*, 2000). As water content progressively decreased below this
7 point, the intensity of the first endotherm was reduced, but remained at
8 almost the same temperature ((

9 Figure 2), until its total disappearance below to 35% of water (Eliasson,
10 1980; Burt *et al.*, 1983; Champenois *et al.*, 1995). Conversely, Sopade,
11 Halley & Junming (2004) reported an increase in the gelatinisation
12 temperature of 1.1°C for a reduction in water content from 50 to 40% wb.
13 At the same time, when water content was lower than 60% the second and
14 third endotherms moved to higher temperatures but at different rates ((

15 Figure 2) and finally merged into a single endotherm above 35%wb (Burt
16 *et al.*, 1983; Champenois *et al.*, 1995). In fact, the starch granules and the
17 gluten will compete for water, which will result in an additional increase in
18 the gelatinisation temperature (Eliasson *et al.*, 1993; Wang, Choi & Kerr,
19 2004). The loss of birefringence observed for very low water content
20 (<25%) and at high temperatures was related to the second endotherm (Burt
21 *et al.*, 1983). A peak at 70°C was observed in the thermogram of a freshly
22 sampled crust, corresponding to the starch crystals that did not gelatinise
23 during baking, in addition to the peak corresponding to the amylose–lipid
24 complex (Primo-Martin *et al.*, 2007).

1 Some studies have also shown that the gelatinisation temperature was
2 affected by the heating rate. Although applicable to potato starch,
3 (Donovan, 1979) observed that the greater the heating rate (2 to 10°C/min),
4 the higher the temperature of the endotherm peak (+2°C). Likewise, Patel
5 & Seetharaman (2006) observed a shift in the swelling of wheat starch
6 granules at higher temperatures when the heating rate increased from 5 to
7 25°C/min. It must be mentioned here that changes in dough viscosity were
8 also delayed by increasing the heating rate from 3 to 9°C/min (Bloksma,
9 1980).

10 To conclude, it can be expected that starch granules present in the
11 superficial layers only partially gelatinise, because of the strong reduction
12 in water content and the more rapid heating rates, which both increase the
13 starch melting temperature. This will influence the rheological properties of
14 dough films during baking and possibly cell growth in the crust. As far as
15 the crust is concerned, it would be interesting to characterise this reaction
16 during simultaneous heating and drying.

17 2.3.2 Gluten coagulation

18 The lower the water content, the higher the denaturation temperature of
19 proteins (Eliasson *et al.*, 1993). For ω -gliadin aqueous solutions for
20 instance, it increased from 117 to 157°C by lowering the water content
21 from 20 to 3%wb (Noel, Parker, Ring & Tatham, 1995). Denaturation is
22 followed by aggregation and, for some proteins, gel formation (Eliasson *et*
23 *al.*, 1993). In contrast to the first stage, this stage is a kinetics-dependent
24 exothermic process: the lower the heating rate, the more advanced the
25 process of aggregation (Myers, 1990).

1 As a consequence of these combined effects, the bread crust showed a
2 minimal decrease in water-extractible proteins, meaning that they were not
3 as aggregated and/or cross-linked as in the crumb (Westerlund, Theander &
4 Aman, 1989). This would undoubtedly affect the mechanical modifications
5 of the gluten network in the superficial layers upon heating. The
6 disappearance of soluble protein was almost complete in wheat gluten and
7 glutenin at 25-30%wb of water content heated at very high rates (25°C/s
8 from 40 to 170°C) (Strecker, Cavalieri, Zollars & Pomeranz, 1995); to the
9 light of this last study, results from Westerlund *et al.* (1989) could be
10 explained to the very low water content encountered in bread crust.

11 The amount of water to be released was also expected to be lower, with
12 possible limitations on other biochemical reactions including starch
13 gelatinisation (Marston & Wannan, 1976; Wang *et al.*, 2004) and/or to
14 water transport (Thorvaldsson & Skjöldebrand, 1998; Mondal & Datta,
15 2008).

16 Glass transition (GT) is also an issue given the low water contents
17 associated with high temperatures (Huang, Haynes, Levine & Slade, 1996)

18 (
19 Figure 2). However, it is commonly accepted that GT usually occurs upon
20 cooling (Cuq *et al.*, 2003) –also see

21 Figure 2, which is outside the scope of this review and is not discussed
22 here. Nevertheless local heat-moisture treatment during baking (sections
23 2.1 and 2.2) undoubtedly affect the consecutive process of GT during post-
24 chilling.

25

1 2.3.3 Maillard reaction

2 Highly reactive compounds are initially produced from this reaction;
3 afterwards, their polymerization yields products of brown colour (Martins,
4 Jongen & van Boekel, 2001) observable at around 105-115°C (Zanoni, Peri
5 & Bruno, 1995a; Broyart, Trystram & Duquenoy, 1998; Wahlby *et al.*,
6 2002). Starch is also consumed during the reaction, leading to a reduction
7 in the starch concentration in the crust compared with the crumb (Cauvain,
8 1998). Finally, some of the desired flavours and aromas of bread, among
9 which 2-Acetyl-1-pyrroline, 4-hydroxy-2,5-dimethyl-3(2H)-furanone, 2,3-
10 butanedione, methional, (E)-2-nonenal, methylpropanal, and 2- and 3-
11 methylbutanal for baguette crust, are also produced, mainly by the Maillard
12 reaction (Zehentbauer & Grosch, 1998a; b; Poinot, Arvisenet, Grua-Priol,
13 Colas, Fillonneau, Le Bail *et al.*, 2008).

14 Low water activity (optimal between 0.4 and 0.8) (Charissou, Ait-Ameur &
15 Birlouez-Aragon, 2007) and high temperatures (commonly above 105°C as
16 mentioned above) accelerated the Maillard reaction. WL and browning
17 were linearly correlated (Wahlby *et al.*, 2002; Purlis & Salvadori, 2007).
18 Independently of the HT mode (natural or forced convection), the lightness
19 of the bread surface decreased as the oven temperature increased (180 to
20 220°C); at even oven air temperatures, forced convection caused higher
21 browning than natural convection (Purlis *et al.*, 2007).

22 Different models based on first order kinetics were proposed to predict the
23 kinetics of colour development. They were dependent on surface
24 temperature alone (Zanoni *et al.*, 1995a) or combined to water content,
25 yielding errors of prediction less than 10% for WL higher than 10% (Purlis

1 *et al.*, 2007) or between 1-24% on biscuits at the end of baking (Broyart *et*
2 *al.*, 1998).

3 The Maillard reaction may also result in toxic compounds, such as
4 acrylamide. Several recent reviews have been focalized in the study of
5 acrylamide formation in cereal products (Sadd & Hamlet, 2005; Konings,
6 Ashby, Hamlet & Thompson, 2007; Claus, Carle & Schieber, 2008) (for
7 further details see the cited reviews).

8 Previous studies correlated its formation to the oven air temperature,
9 although the key variable is the exact local temperature at the dough
10 surface which depends on many variables other than the oven air
11 temperature. The amount of acrylamide in the crust of bread, flat bread, dry
12 starch system and dried rye-based flat bread rose with longer baking times
13 and higher oven temperatures (Brathen & Knutsen, 2005). A similar effect
14 was reported by Ahrne *et al.* (2007).

15

16 **2.4 Rheological evolution**

17 The rheological properties of dough change significantly during baking,
18 mainly as the result of the temperature-induced changes to the molecular
19 structures. Between 26 and 60°C, the viscosity of dough decreased by a
20 factor of 5 (Bloksma, 1990), supporting the deformation of dough films.
21 The water content is a key factor since a variation of 4% induced a
22 variation in viscosity by a factor of 2 (Bloksma, 1990). Above 60°C,
23 viscosity increased by a factor of 10, and the starch granules inflated and
24 the gluten molecules were polymerized, damaging dough extensibility
25 (Bloksma, 1990). Moreover, the higher the heating rate, the lower the

1 minimum viscosity and the higher the temperature where this minimum
2 viscosity occurred (Bloksma, 1980).

3 Although starch gelatinisation and protein denaturation are responsible for
4 the loss of extensibility of the crumb, this should not apply to the crust
5 (section 2.3.1): starch gelatinisation is expected to be delayed by the high
6 heating rate and the low water content encountered in the crust and this
7 would favour low levels of viscosity. It is thus most probable that the loss
8 of extensibility of superficial layers during baking is due to dehydration,
9 although this point is not clear in the literature.

10 The rheological properties of bread dough have been widely characterised
11 experimentally but generally not in conditions realistically representing the
12 baking process, especially regarding the crust. Firstly, viscosity and
13 eventually elasticity have been thoroughly measured at ambient and/or
14 constant temperatures, but rarely during dynamic heating. When applied,
15 heating rates have been appropriate to the bread core (Collar, Bollain &
16 Rosell, 2007), and rarely to the crust, the highest comparable values being 9
17 to 11°C/min (Bloksma, 1980; Singh & Bhattacharya, 2005). Secondly,
18 bread dough has been characterised at very low uniaxial shear rates
19 (between 10^{-2} and 10^{-3} s⁻¹) (Bloksma, 1990) and more recently under
20 biaxial extension at rates of 5×10^{-2} s⁻¹ (Rouille, Della Valle, Lefebvre,
21 Sliwinski & vanVliet, 2005) and 10^{-1} s⁻¹ (Dobraszczyk *et al.*, 2008). Most
22 of these strain rates failed to reproduce those encountered during baking (1
23 to 2×10^{-3} s⁻¹) (Bloksma, 1990). With the exception of biaxial extension
24 (Dobraszczyk & Morgenstern, 2003), other tests used in combination with
25 dynamic heating only approximately reproduce the expected deformation

1 of dough films over a gas bubble during baking. Finally, rheological
2 measurements applicable to the crust should ideally be conducted under
3 dynamic drying; again most of the data available were obtained at a
4 constant water content, with levels relevant to the dough.

5 In the current mathematical models of baking, the mechanics are usually
6 simplified and the dough considered as viscous only (Lostie *et al.*, 2002b;
7 Lucas *et al.*, 2009) . Viscosity was not dependent on water content and was
8 at best temperature-dependent. Nevertheless, fair agreement between
9 simulation and experiment was usually obtained due to the numerous
10 parameters to be adjusted and because the validation was based on overall
11 measurement of the oven-rise (Lostie *et al.*, 2002a; Zhang *et al.*, 2006), and
12 rarely on local measurements (Lucas *et al.*, 2009). The simplified
13 rheological behaviour of dough (viscous rather than viscoelastic) used in
14 these models could be responsible for the discrepancies in total height
15 (Lostie *et al.*, 2002a) or in the intensity of local compression in the crumb
16 (Lucas *et al.*, 2009).

17

18 **2.5 Cell growth**

19 Because of the proximity of the boundary with the oven air, gases easily
20 escape the crust and the pressure remains close to the atmospheric pressure
21 (see pressure profiles calculated by Zhang *et al.* (2006) and Lucas *et al.*
22 (2009)). Additionally, the loss of extensibility of dough films is expected to
23 be more rapid, presumably because of the great reduction in water content.
24 Thus, one reason to explain the smaller size of cells in the crust than in the
25 crumb (

1 Figure 3) is that the forces favouring expansion are not sufficient for cell
2 growth, although the full mechanism underlying cell growth warrants in
3 depth study.

4 Moreover, the surface layers cannot deform fast enough to accommodate
5 the core expansion. This leads to a domed shaped top surface, and also to
6 similar curvature of the internal structures, *i.e.* elliptical shapes of cells
7 observed during baking (Whitworth & Alava, 2004). In fact, when setting
8 of the surface layers occurred early compared to the heating at core (

9 Figure 4f), two opposite forces were exerted on the intermediate regions,
10 which tended to be compressed (

11 Figure 4d), the extent of compression being related to the time elapsed
12 between stiffening of dough films and their rupture (Jefferson, Lacey &
13 Sadd, 2006; Lucas *et al.*, 2009).

14 The dimension, shape and number of gas cells in the crumb have been
15 studied by various imaging techniques; comparatively the crust was subject
16 of few studies (Datta, Sahin, Sumnu & Keskin, 2006; Zhang *et al.*, 2006;
17 Primo-Martin *et al.*, 2007). It must be emphasized that the majority of
18 microscopy techniques are destructive and do not allow dynamic
19 observation of a process such as baking. Other techniques providing
20 dynamic measurements often average the bubble size distribution over the
21 whole dough sample, which is relevant in the case of a quite homogeneous
22 alveolar structure as expected during proving (Leroy, Fan, Strybulevych,
23 Belido, Page & Scanlon, 2008). Another requirement for imaging is high
24 spatial resolution, given that the mean cell size in the crust is around
25 100 μ m. Among the techniques available, X-ray synchrotron seems to be

1 the most appropriate. A quantitative, dynamic study of the alveolar
2 structure in the crumb during baking was recently reported (Babin, Della
3 Valle, Chiron, Cloetens, Hoszowska, Pernot *et al.*, 2006). The feasibility
4 for the crust still needs to be tested. It would require warming the sample at
5 higher rates and using higher frequencies of acquisition than those used for
6 the crumb, although the signal to noise ratio would be lower due to low
7 water content and low levels of signal accumulation.

8

9 **3 How the crust affects other mechanisms during baking**

10 **3.1 Mechanical constraint to crumb expansion, both locally and** 11 **overall**

12 3.1.1 Loss of extensibility

13 The cessation of overall expansion was experimentally related to the
14 occurrence of a dry surface during sponge cake (Lostie *et al.*, 2002b) and
15 bread (Zanoni *et al.*, 1993) baking. Similarly, protecting dough samples
16 with paraffin oil to prevent dehydration allowed continuous expansion until
17 100°C, whereas it ceased between 36 and 62°C (Le Meste *et al.*, 1992).

18 Using magnetic resonance imaging (MRI) Wagner, Quellec, Trystram &
19 Lucas (2008a) recently reported that if the crust was set early, and even if
20 total expansion had ceased, local expansion could continue (

21 Figure 4a- c), especially in the colder areas which had not already expanded
22 (

23 Figure 4f). These areas expanded to the detriment of others which were
24 then compressed (

1 Figure 4d). Such compression was accompanied by the disappearance of
2 the largest bubbles, suggesting that it involved the weakest structures from
3 a mechanical view-point. (Zhang, Lucas, Doursat, Flick & Wagner, 2007)
4 developed a device with a fabric lid which made it possible to stop the
5 oven-rise at different heights. Using MRI they showed that the later the
6 oven-rise was stopped, the deeper the location of the squeezed crumb. Such
7 a trend could be reproduced with a model of baking (Figure 4a-c) which in turn made it possible to relate the occurrence of
8 compression to the mechanical properties of dough films (already ruptured
9 but not already stiffened). Similarly, in the theoretical approach developed
10 by Jefferson *et al.* (2006), the more a cell is set when its film fractured, the
11 less squashing took place and the lower the final density in that part of the
12 bread. Likewise, Hayman (1998) suggested that crust formation resulted in
13 an increase in the internal pressure in the unbaked portion of the dough,
14 imposing additional stress on the dough films, and ultimately leading to
15 bubble coalescence and to a coarser crumb structure. If no crust was
16 formed, a fine crumb structure was expected, which was evidenced from
17 cross sections of loaves produced with their electrical resistance oven
18 (ERO) for a wide range of wheat flours.
19
20 Additionally, MRI and X-ray images showed how crust rupture allowed
21 prolongation of the local expansion and also contributed to strong spatial
22 heterogeneity in crumb expansion (Whitworth *et al.*, 2004; Wagner *et al.*,
23 2008a).
24 Crust setting has rarely been taken into account in the models of baking. To
25 do so, the rheological properties of dough should be dependent on both

1 temperature and water content (section 2.4). Moreover, a proper description
2 would be two-dimensional (Zhang *et al.*, 2006). In current models of
3 unidirectional transport and expansion, the cessation of oven-rise was
4 “successfully” reproduced by artificially imposing nil displacement of the
5 outer boundary after a certain baking time –adjusted on experimental data
6 *e.g.* (Lucas *et al.*, 2009), or by using high values of viscosity at high
7 temperatures *e.g.* (Lostie *et al.*, 2002a).

8 3.1.2 Lower permeability to gases

9 The constraints to crumb expansion may also be generated by low
10 permeability of the crust to gases, through the pressure build-up. Almost no
11 pressure build-up was obtained from baking models when high
12 permeability values with uniform distribution through the dough were used
13 (Zhang *et al.*, 2006). The authors finally retained in their simulations lower
14 permeability for the “crust” (the region of interest was not defined) than for
15 the crumb. The effect of low permeability of the surface layers on the
16 pressure build-up was recently evidenced by Grenier, Le Ray & Lucas
17 (2009).

18 It is well known that the permeability of a porous medium is affected by the
19 pore fraction and structure. Very little information is available in the
20 literature for the dough/crumb, and some of it is controversial. Baker
21 (1939) related the gas flow to cell size in commercial white bread, but no
22 permeability values are available in this study. Dough permeability was
23 directly related to porosity, whatever the water (15-50%wb) and fat (2-8%)
24 contents (Goedeken, 1993). Based on this study, the permeability of typical
25 crumb (75% of porosity) was estimated at around $2.2 \times 10^{-11} \text{ m}^2$, and of

1 typical crust (40% of porosity) around 10^{-12} m². These orders of magnitude
2 were used for crumb (10^{-11} m²) and crust (2.5×10^{-12} m²) in the baking
3 model developed by Zhang *et al.* (2006). All other baking models
4 considered uniform permeability through the product (Lostie *et al.*, 2002a;
5 Lucas *et al.*, 2009), which makes their simulations of CO₂ release and
6 oven-rise questionable.

7 3.1.3 Secondary effect on the gas released (through pressure build-up)

8
9 Zhang *et al.* (2007) monitored the CO₂ released during baking and
10 observed an induction period followed by a sudden, linear increase in CO₂
11 release, ending with a plateau zone. They also found that the earlier the
12 oven-rise was stopped, the shorter the induction period. Similar trends
13 could be reproduced by a mathematical model of baking, which showed in
14 addition that film rupture was necessary but not sufficient to demonstrate
15 CO₂ release and that it must be accompanied by a pressure build-up similar
16 to that stemming from an early cessation of the oven-rise. Similarly, Lucas,
17 Le Ray, Peu, Wagner & Picard (2007) found lower CO₂ release for lower
18 oven air temperatures, which delayed the formation of the crust.

19 CO₂ was considered to be the main gas responsible for oven-rise (Bloksma,
20 1990). Leakage of CO₂ obviously implies a decreasing amount of gas in
21 cells and presumably a lower potential for cell growth. Interpreting the CO₂
22 release is however a little more complicated since it also reveals a build-up
23 in internal pressure, which is the driving force for cell growth provided that
24 the dough films are still deformable. The net balance between these two
25 antagonistic mechanisms has not been assessed to date. CO₂ is also

1 regarded as a vector of transport of the aromatic compounds (Eliasson *et*
2 *al.*, 1993). For all these reasons, the mechanisms governing CO₂ release
3 warrant further investigation for a thorough understanding and a clear
4 identification of the key factors.

5 **3.2 A barrier to heat and water transport**

6 Wahlby *et al.* (2002) compared the WL of buns reheated with and without
7 crust. Whatever the heating time, WL without crust was three times greater
8 than with crust. This was attributed to the differences in crust and crumb
9 porosity. Breads baked in an impingement or hybrid oven (forced
10 convection combined with microwave) lose less water than conventionally
11 baked breads (Patel, Waniska & Seetharaman, 2005). This was attributed to
12 early crust formation in the former case. Although this effect on WL is
13 commonly accepted (Eliasson *et al.*, 1993), the underlying mechanisms
14 have only recently been studied with the aid of models (Lostie *et al.*, 2004;
15 Zhang *et al.*, 2008).

16 As reported in section 2.2, HT governed the progress of the vaporisation
17 front in the surface layers and thus WL during baking. As the front went
18 deeper, the resistance to HT increased and slowed down the WL. Similarly,
19 high porosity in the surface layers increased this resistance (Vanin, Grenier,
20 Doursat, Flick, Trystram & Lucas, 2009) since the same amount of water
21 was distributed over a thicker area. Changes in thermal conductivity could
22 also affect the resistance to HT in the surface layers and in turn the WL
23 (Vanin *et al.*, 2009). Thermal conductivity of the dough/crumb decreased
24 with decreasing water content and increasing porosity (Rask, 1989; Zanoni,
25 Peri & Gianotti, 1995b; Jury *et al.*, 2007). However, conductivity measured

1 on crust and crumb samples has been found to be very close (Jury *et al.*,
2 2007), meaning that the effects of porosity and water content may
3 compensate for each other.

4 Water transport to the core by the evaporation-condensation-diffusion
5 mechanism also contributed to the dehydration of superficial layers, but to
6 a lower extent; it was theoretically favoured by higher porosity in the
7 crumb (Zhang *et al.*, 2008).

8 It must be remembered here that the porosity profile which affects the crust
9 thickening through the mechanisms described above is itself greatly
10 affected by fairly early setting of the crust (see section 3.1.1, and also
11 Figure 4a-c). A thorough understanding of these strongly interlinked
12 mechanisms is necessary for fine control of crust formation, WL and local
13 density together (Vanin *et al.*, 2009).

14

15 **4 Conclusion**

16 **4.1 Can a definition of the “crust” region be proposed?**

17 An accurate definition of the spatial domain comprising the crust remains
18 necessary for any further study. Changes in its properties are believed to be
19 gradual, making it difficult to define a boundary with the crumb beneath.

20 A crust is commonly referred to as a dry, hard, dense, coloured zone,
21 following exposure to high temperatures: “... a hard, vitreous surface layer
22 formed of collapsed crumb pore walls” (Eliasson *et al.*, 1993); “...a denser,
23 darker surface parts bread, near to its surface” (Jefferson *et al.*, 2006). It
24 must be remembered that low water content and high temperature are

1 determinants (but not the only) of many of the other features (colour,
2 porosity, molecular structures, hardness...).

3 Only a few experimental studies gave their criterion separating the crust
4 from the crumb. The crust sample was often unique, distinguishable from
5 the crumb sample(s) by its darker colour (visual criterion, *e.g.* (Lind *et al.*,
6 1991)) or its more cohesive, harder structure (mechanical property *e.g.*
7 (Westerlund *et al.*, 1989)). Many factors, including lower water content,
8 higher density, smaller and more elongated cells, vitreous transition, etc...
9 may contribute together or separately to a distinct mechanical behaviour.

10 Mechanical separation may also originate from constraints created during
11 cooling *e.g.* (Le Bail, Monteau, Lucas, Chargelègue & Reverdy, 2005) in
12 the case of part-baked breads. (Zanoni *et al.*, 1993) separated the crust by
13 quick freezing which caused rupture between the “crust” and “crumb”. All
14 this makes the mechanical criterion not very reliable when comparing
15 results from various studies. The same applies to colour, with the effect of
16 small carbohydrates.

17 Surprisingly, despite these raw criteria, the properties measured on crust
18 samples are quite consistent between studies (

19 Figure 1). Likewise, thickness of the crust has been reported to increase
20 linearly with baking time (Zanoni *et al.*, 1993; Wiggins, 1998). However,
21 the number of studies is not sufficient to conclude at this stage.

22 From a theoretical point-of-view, the crust boundary can be refined by
23 using a threshold value applied to a criterion such as density or water
24 content. Jefferson *et al.* (2006) characterised crust thickness as the distance
25 from the surface where the final density was the same as the original dough

1 density and Zhang *et al.* (2008) from the top surface to the point where the
2 water flowed most rapidly, *i.e.* the vaporisation front. A criterion with
3 physical relevance to the threshold should represent a sharp change
4 between the surface and the core, as water content or temperature do (
5 Figure 4e, f). Porosity presents either no sharp change (
6 Figure 4a) or many sharp changes (
7 Figure 4c) between the surface and core, which makes this criterion hardly
8 reliable. Corresponding experimental profiles of water content and
9 temperature are few and thus it is a definition that could not be applied at
10 the experimental level to date. All this supports the need to develop a non-
11 invasive, dynamic technique to study the specific behaviour of surface
12 layers, with the special requirement of high spatial resolution.

13 **4.2 Need for further research**

14 Superficial bread layers differ from core layers of the crumb mainly in their
15 dynamics during baking. Lack of published data and information on
16 prevailing mechanisms in the superficial layers of bread have prevented
17 modelling studies from considering crust setting and its effects on heat,
18 mass transport and cell growth in the crumb, as well as the full
19 understanding and control of baking.

20 On the one hand, this review has shown that the knowledge acquired
21 regarding the crumb cannot be extrapolated to superficial layers with
22 confidence, especially because the mechanisms are highly interrelated,
23 often working antagonistically and because they are highly sensitive to
24 temperature and water content. The identification of prevailing mechanisms
25 thus remains an issue for future studies.

1 On the other hand, we have attempted to fill the gap in the published data
2 through the different enclosed charts. We have also shown that methods of
3 measurement for monitoring the dynamics (temperature, water content) in
4 the superficial layers present limitations in terms of convenience and
5 accuracy, and there is a real need to develop, or sometimes simply
6 implement, non-intrusive, continuous techniques of measurement. The
7 dynamics impact on the microstructures and hence the main properties of
8 the crust. Understanding of the underlying reactions has been inferred from
9 measurements performed on samples of different water content, but very
10 few studies have related heating to drying. There is therefore a real
11 challenge to reproduce these dynamics with miniaturisation inside the
12 instrument of analysis (rheometer or X-ray synchrotron for instance).
13 Aguilera (2005) recently emphasized the possibilities offered by the recent
14 advances in imaging to dynamically study of microstructures during
15 processing. All these developments will contribute to providing
16 information of higher spatial resolution and to a clearer definition of the
17 crust region, a prerequisite for further studies in this area.

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23
24 **Table and figure list**

25
26 Figure 1: Water content in crust (hollow symbols) and crumb (filled
27 symbols) during baking from different literature sources.

1

2 Figure 2: Dependence on water content of gelatinisation temperatures of
3 wheat starch-water mixtures and GT of gluten and bread as demonstrated
4 by DSC from different literature sources.

5

6 Figure 3: Microstructure of bread baked in microwave-infrared
7 combination oven observed by SEM at $\times 50$ for (a) crumb, (b) crust. Bars
8 represent 300 μm . Source: Datta *et al.* (2006). Reprinted from Journal of
9 Food Engineering, 79, Datta, A.K., Sahin, S., Sumnu, G., & Keskin, S.O.,
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12

13 Figure 4: Porosity profile for different final total heights (45(a), 50(b) and
14 55(c) mm) after 45 min of baking. Porosity (d), water content (e) and
15 temperature (f) profiles at different baking times for a final height of 60
16 mm. Adapted from Zhang *et al.* (2007) and Lucas *et al.* (2009).

17

18 Table 1: Heating rates for different cereal products and baking conditions at
19 bread surface and core.

20

21

Table 1

Product	Mass of dough/batter (g)	Surfaces exposed to heat transfer	Position of temperature in dough/batter	Oven air temperature (C°)	Heating rate (°C/min)	Reference
Bread	200	top bottom	top surface	185	7.7	(Wagner <i>et al.</i> , 2008)
			bottom surface		2.6	
			centre		2.4	
Bread	341	all	top surface	203	11.3	(Zanoni <i>et al.</i> , 1993)
			bottom surface		9.5	
			at 1cm beneath the top surface		2.6	
Bread	-	all	top surface	210	10.3*	(Thorvaldsson <i>et al.</i> , 1996)
			mid-width		3.9*	
			centre		1.8*	
Pan bread	-	-	surface	220	8.8	(Dogan, 2002)
Francaia	-	-			14.4	
Bread	1.5L	all	top surface	225	6.7	(Thorvaldsson <i>et al.</i> , 1998)
			bottom surface		4.4	
Bread	760	all	side surface	235	7.4	(Marston <i>et al.</i> , 1976)
			centre		2.8	
Biscuit	-	all	centre	300	75.0** (400g/kg dry air)	(Chevallier)

				300	61.7** (20g/kg dry air)	<i>et al., 2002)</i>
				240	44.7** (200g/kg dry air)	
				180	19.6** (20g/kg dry air)	
Sponge cake	400-600	top	top surface	200	0.5	(Lostie <i>et al., 2002b)</i>

“-“ refers to missing information

* data from reheated samples

** with different relative air humidity

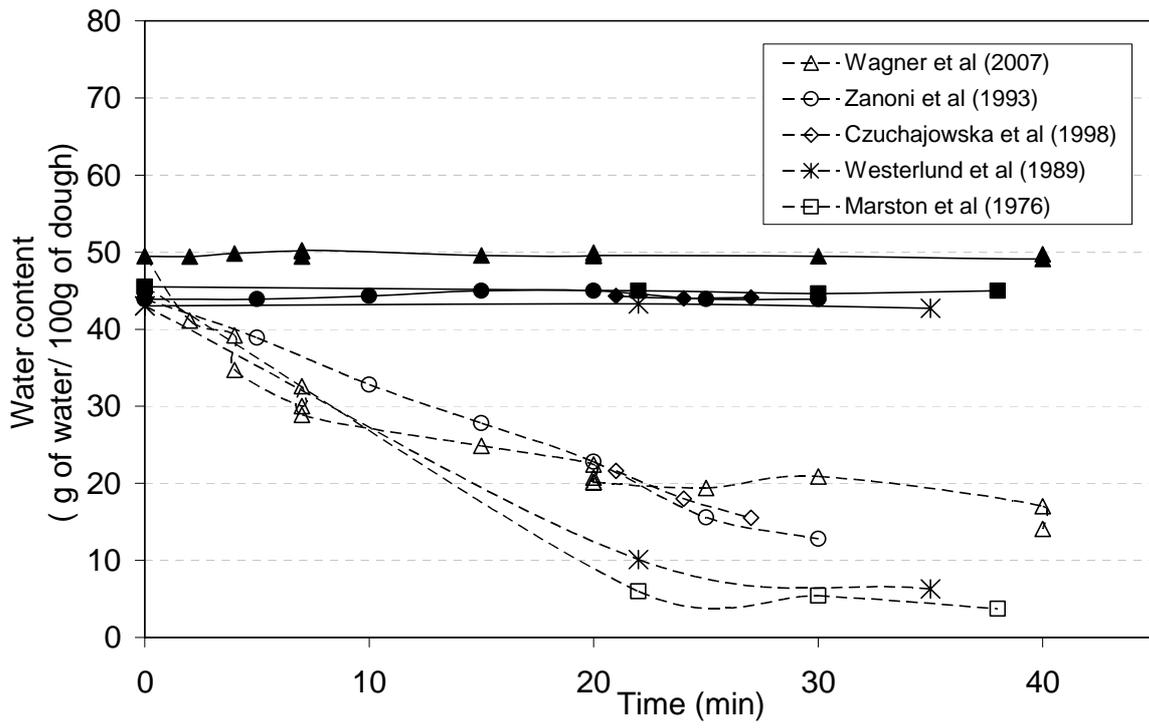


Figure 1

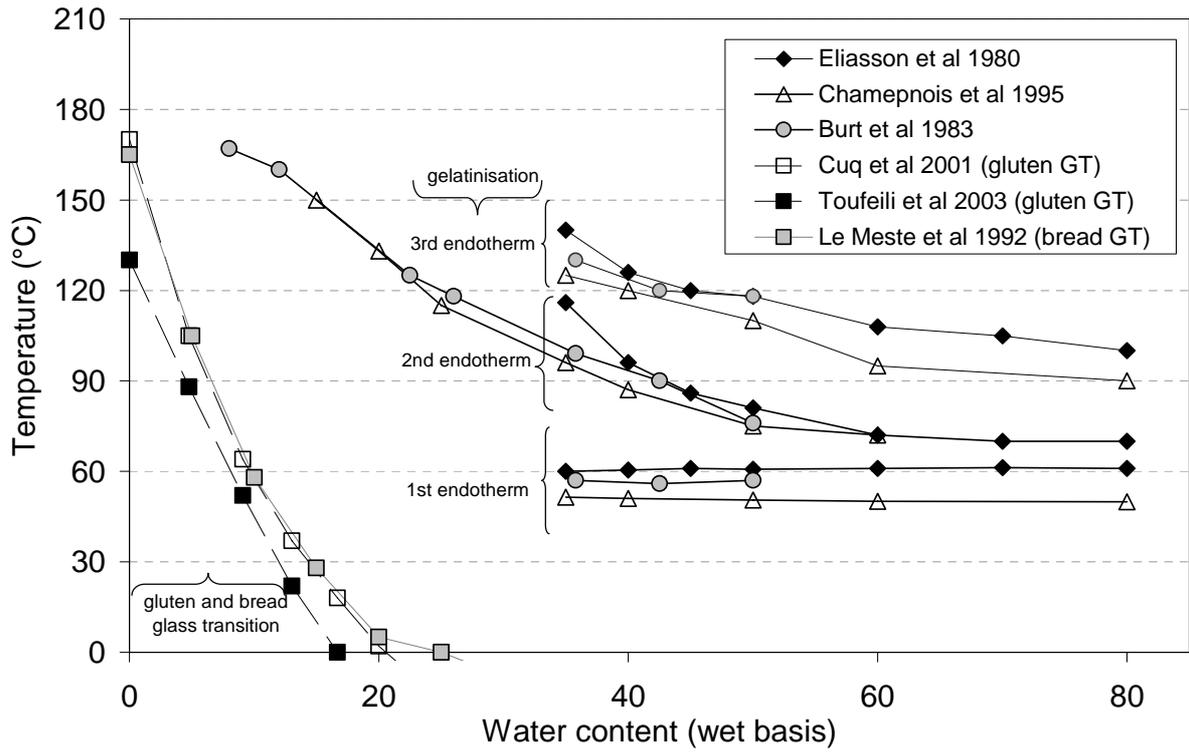
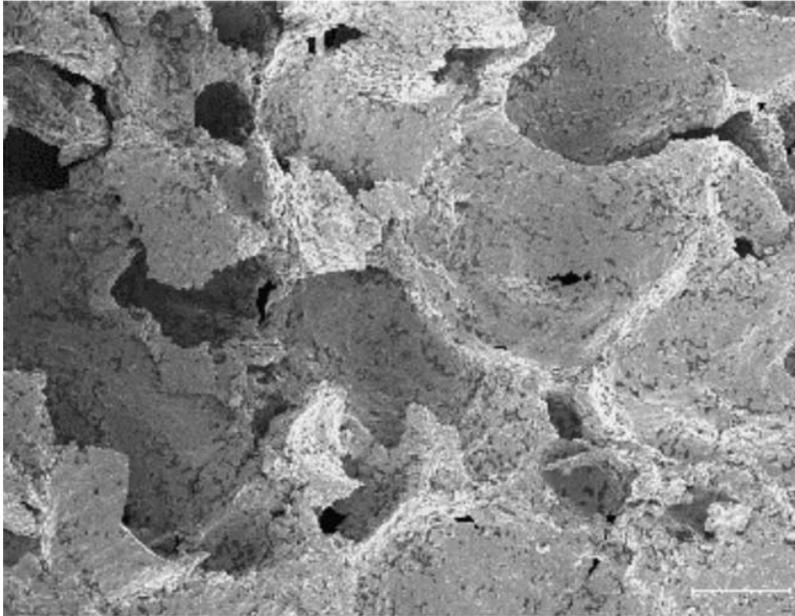
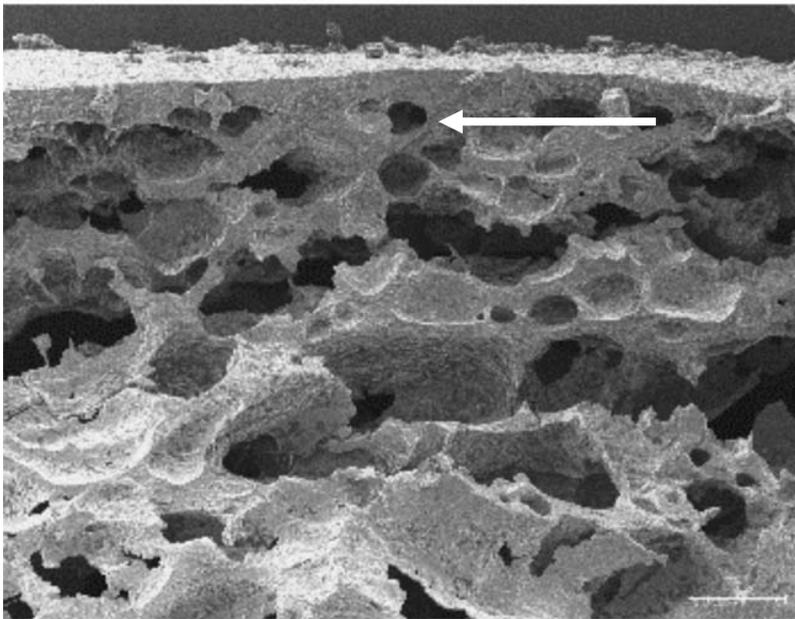


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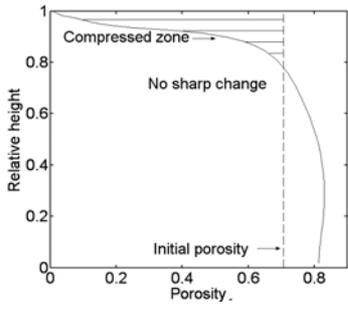


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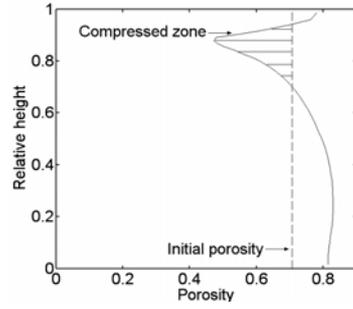


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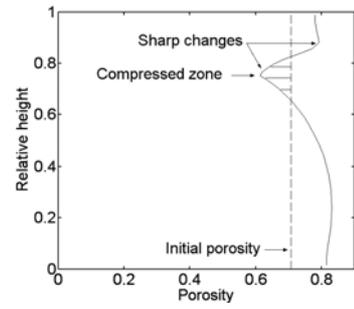
Figure 3



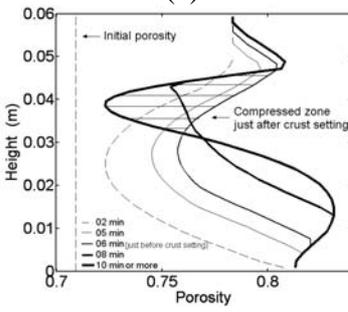
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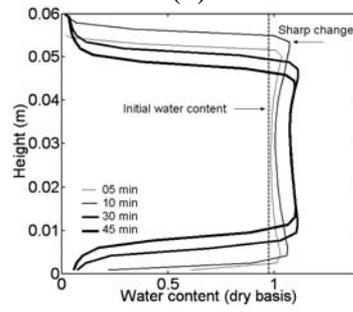
(b)



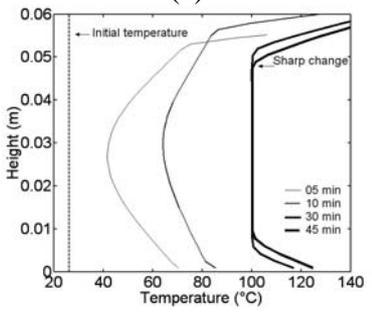
(c)



(d)



(e)



(f)

Figure 4