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Tensile strength of tablets containing two materials with a different compaction behaviour

B. van Veen[a,*], K. van der Voort Maarschalk[b], G.K. Bolhuis[a], K. Zuurman[a], H.W. Frijlink[a]

[a] *Department of Pharmaceutical Technology and Biopharmacy, University of Groningen, Antonius Deusinglaan 1, 9713 AV Groningen, The Netherlands*

[b] *N.V. Organon, Molenstraat 110, 5342 CC Oss, The Netherlands*

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Abstract

The tensile strength of tablets compressed from binary mixtures is in general not linearly related to the strength of tablets prepared from single materials; in many cases it shows a decreased tensile strength relative to interpolation. The materials used in this study, sodium chloride and pregelatinised starch, are both plastically deforming materials, but have a different densification and relaxation behaviour. The yield pressure of the binary mixtures shows an almost linear relationship. As an effect of their lower yield pressure, starch particles yield earlier than sodium chloride particles. The following enclosure prevents some sodium chloride particles to yield or crack. The relaxation of the tablets is higher than the relaxation calculated by linear interpolation of the relaxation behaviour of the two pure materials. The difference between the measured porosity expansion and the data obtained by linear interpolation can be considered as a measure for the reduced interparticle bonding. SEM-photographs indicate that the reduced interparticle bonding is caused by the low adhesive forces. The measured decrease of the tensile strength of the tablets is also considered to be the result of reduced interparticle bonding. In this paper it is shown that there exists a similar relationship between the tensile strength reduction and the percentage of starch on the one hand and the extra porosity expansion and the starch percentage on the other hand. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Tablet strength; Binary mixture; Densification; Interparticle bonding; Relaxation

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1. Introduction

Tablets produced in the pharmaceutical industry commonly consist of more than one component. The mechanical strength of a tablet depends on both formulation and processing parameters. Even at constant processing parameters, the strength of tablets compressed from binary mixtures can often not be predicted from the compaction properties of the starting materials, because interactions between the materials may occur during the compaction process (Vromans and Lerk, 1988).

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* Corresponding author. Tel.: +31-50-3633282; fax: +31-50-3632500.

E-mail address: b.van.veen@farm.rug.nl (B. van Veen).

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Tablet formation is the result of densification, interparticle bonding and relaxation. Each component has its own compaction behaviour. After rearrangement of the particles and building up of the pressure, the particles of the single materials behave brittle or viscoelastic (Duberg and Nyström, 1986; Van der Voort Maarschalk and Bolhuis, 1998). Additionally, the deformation behaviour depends on other factors like particle size in relation to its critical brittle/ductile transition particle size (Roberts et al., 1989) and compaction velocity (Roberts and Rowe, 1985). After release of the applied load, the tablet shows a certain amount of relaxation before reaching its final porosity.

Several investigators examined the compaction behaviour of binary mixtures. The effects of different parameters, such as compaction behaviour (Sheikh-Salem and Fell, 1981), surface area (Adolfsson et al., 1998) and compaction speed (Cook and Summers, 1990; Garr and Rubinstein, 1991), on the final tensile strength of the tablets compressed from blends were reported. In most cases, the strength of the tablets compressed from the blend was found to be lower than the strength calculated by interpolation of the strength of tablets prepared from the pure materials.

The composition of the powder mixture is directly related to a number of tablet properties, such as tablet strength. Furthermore, it is known that the tensile strength of tablets correlates with the porosity according to, e.g. the Ryshkewitch–Duckworth equation (Duckworth, 1953). In order to compare the tensile strength of tablets compressed from different blends of two materials, it is necessary to use volume fractions instead of weight fractions, because it may be expected that the three-dimensional structure of the tablet is more important than the weight ratio of the components (Bangudu and Pilpel, 1984). Moreover, a constant porosity is necessary to compare the tensile strength of tablets compressed from the mixtures with different volume percentages.

This study was performed to investigate differences between tensile strength of tablets compressed from blends of two materials and the tensile strength of tablets compressed from the individual components. These differences will be related to differences in densification, interparticle bonding and tablet relaxation. The materials chosen were two plastically deforming materials, but with different densification and relaxation behaviours (Van der Voort Maarschalk et al., 1997). The final tablet porosity of sodium chloride is almost completely determined by the densification stage, whereas relaxation hardly occurs. In contrast, the ultimate tablet porosity of pregelatinised starch is the effect of both densification and relaxation behaviour (Van der Voort Maarschalk et al., 1997).

2. Materials and methods

The materials used were sodium chloride (glidant-free material, Akzo Nobel, Hengelo, The Netherlands) and pregelatinised potato starch (Paselli WA4, Avebe, Foxhol, The Netherlands). Before use sodium chloride was milled (Moulinex, Birmingham, UK) for a short period of time. From both materials the sieve fraction between 106 and 212 μm was obtained using an Air Jet Sieve (Alpine, Augsburg, Germany) equipped with USA Standard testing sieves (W.B. Tyler, Mentor, OH, USA).

Before use the materials were stored at a temperature of 20°C and a relative humidity of 60% for a period of at least 4 days.

The true density of the 106–212-μm fractions was measured by helium pycnometry (Quantachrome, Syosset, NY, USA) at a temperature of 20°C. The true densities of sodium chloride and pregelatinised potato starch were 2239 and 1486 kg m^{-3}, respectively.

The binary mixtures were prepared in volume percentages; mixing was performed with a Turbula mixer, model 2P (W.A. Bachofen, Basle, Switzerland) at 90 rpm for a period of 15 min.

Tablets (round, flat, diameter 13 mm, weight 500 mg) were compressed on a compaction simulator (ESH, Brierley Hill, UK) with a constant compaction speed of 3 mm s^{-1}. The compaction pressures varied between 10 and 350 MPa. The upper punch displacement were sine waves with different amplitudes in order to obtain the different compaction pressures. The lower punch was stationary during compaction. The ejection time was always 10 s. After ejection the tablets were stored for at least 14 h in a controlled climate chamber (Heraeus, Hanau, Germany) at a temperature of 20°C and a relative humidity of 60%.

Tablet dimensions were measured with an electronic micrometer (Mitutoyo, Tokyo, Japan) and the tablets were weighed on an analytical balance (Mettler-Toledo, Greifensee, Switzerland).

The crushing strength of the tablets was measured with a Schleuniger 4N strength tester (Dr Schleuniger Productronic, Soloturn, Switzerland). Crushing strengths over 300 N were measured with the compaction simulator as described previously (Van der Voort Maarschalk et al., 1996a). The tensile strength (S) of the tablets was calculated according to Fell and Newton (1968). The tensile strength was calculated for at least 40 tablets with different porosities to determine the Ryshkewitch–Duckworth relation (Duckworth, 1953) between the tensile strength and the tablet porosity for every binary mixture containing a different percentage pregelatinised starch:

$$S = S_0 \cdot e^{-k \cdot \varepsilon} \quad (1)$$

where S_0 is the tensile strength at zero porosity, ε the porosity and k a constant. k describes the bonding capacity (Van der Voort Maarschalk et al., 1996b) and indicates the effect of a change in porosity on the tensile strength. From these Ryskewitch–Duckworth relations the tensile strength at a porosity of 15% was calculated for every blend containing a different percentage pregelatinised starch.

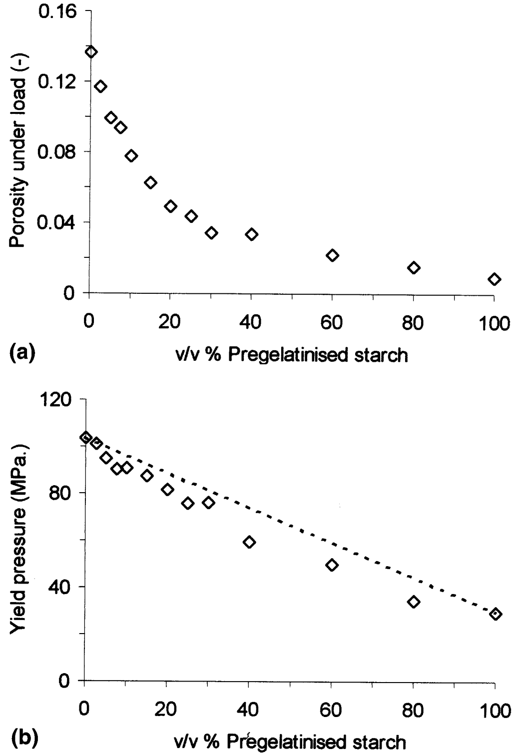

Fig. 1. a: Porosity under load of different binary mixtures of sodium chloride and pregelatinised starch to gain tablets with a final porosity of 15%. b: Yield pressure of sodium chloride, pregelatinised starch and their mixtures (symbols) and the yield pressure of the binary mixtures calculated by linear interpolation (dotted line).

Yield pressure (P_y) of the two materials and the binary mixtures were derived from the force displacement profiles according to Heckel (1961a,b). Linear interpolation was performed in the porosity range between 15 and 35%.

3. Results and discussion

3.1. Densification of the binary powder mixtures

During powder densification, the porosity of a powder bed decreases. If the rearrangement of particles of the different blends is considered as a non-dominant factor, the densification can be studied by both the porosity under load and the yield pressure. Fig. 1a reflects the porosity under load of mixtures of sodium chloride with the different percentages pregelatinised starch. The porosity under load, using compaction pressures to obtain tablets with a final porosity of 15% after relaxation, decreases. Moreover, the slope decreases upon increasing pregelatinised starch concentration. Obviously, the largest influence of the pregelatinised starch particles on the densification of the sodium chloride particles occurs at low starch fractions.

Fig. 1b shows the yield pressure of sodium chloride, pregelatinised starch and their binary mixtures. The yield pressure of the two single materials illustrates the difference in densification behaviour. As reported previously, sodium chloride has a significantly higher yield pressure than pregelatinised starch (Duberg and Nyström, 1985; Van der Voort Maarschalk et al., 1997). The high yield pressure of sodium chloride illustrates its difficult densification. The figure shows that the second component, pregelatinised starch, with the lowest yield pressure enhances the densification of the powder blends. This results in a lower porosity under pressure for the binary mixtures than for pure sodium chloride. A similar effect was found by Cook and Summers (1990) for a blend of aspirin and Starch 1500.

If there would be no mutual interactions on the individual densification behaviour of the components, the yield pressure of a mixture ($P_{y,mix}$) can be described by linear interpolation (dotted line, Fig. 1b) of the yield pressures of each of the two materials (P_{NaCl}, P_{starch}):

$$P_{y,mix} = P_{NaCl} \cdot \varphi_{NaCl} + P_{starch} \cdot \varphi_{starch} \quad (2)$$

with φ_{NaCl} and φ_{starch} being the volume fractions sodium chloride and pregelatinised starch, respectively. The explanation of the small deviations from linearity of the data in Fig. 1b with Eq. (2) can be found from SEM-photographs of the cross-sections of the tablets (Fig. 2a–c). All visual pregelatinised starch and sodium chloride particles in binary mixtures containing 10% (Fig. 2a) or 20% pregelatinised starch (Fig. 2b) are yielded and/or cracked. The SEM picture of tablets compressed from a blend containing 40% pregelatinised starch (Fig. 2c) shows that all the starch particles are deformed. However, a number of the sodium chloride particles still have their original shape and are not cracked, even though the compaction pressure was higher than the yield pressure. Obviously, the starch particles, which are arranged around the sodium chloride particles, prevent these sodium chloride particles to become affected to a large extent by the compaction process. Thereby, preventing them to yield or crack. This explains that the measured yield pressures of the blends are somewhat lower than those described by Eq. (2). The difference in yield pressure between the two components is responsible for this phenomenon. In a binary mixture of sodium chloride and pregelatinised starch under the given conditions, a sodium chloride particle will only yield if it is in direct contact with another sodium chloride particle. On the other hand, it should be realised that the majority of the particles in the blends are yielded during the densification of the powder. Therefore, the deviations from linearity are small.

Although the particle size of sodium chloride is larger than its critical particle diameter of 35 μm (Roberts et al., 1989), the particles possess a low degree of fragmentation at high pressures (Alderborn et al., 1985). Under high pressures and close packing of the particles, there is hardly any possibility for the particles to rearrange. It may therefore be assumed that this small fragmentation has only a minor influence on the eventual tensile strength.

3.2. Relaxation of the tablets

The relaxation of tablets can be quantified in different ways. It can be reflected by an increase in tablet height or volume after compression (Doelker, 1993). Van der Voort Maarschalk et al. (1996a) suggested that tablet relaxation is the result of two phenomena: a decrease in material density and an increase in tablet porosity. In general the compression-induced increase in material density is fully reversible. The increase in tablet porosity occurs during and after release of the pressure from the tablet. The porosity expansion ($\Delta\varepsilon$) is given by:

$$\Delta\varepsilon = \varepsilon - \varepsilon_{min} \quad (3)$$

where ε is the tablet porosity after relaxation and ε_{min} is the porosity under load. ε_{min} is zero if the porosity under load was negative as an effect of the increase of material density. Just like previously found for single materials (Van der Voort Maarschalk et al., 1996b), the porosity expansion for all the different blends of sodium chloride and pregelatinised starch was found to be independent of the compaction pressures used.

Fig. 3 depicts the relationship between the percentage-pregelatinised starch and the porosity expansion for tablets compressed from blends of sodium chloride and pregelatinised starch. In contrast to tablets compressed from pure pregela-

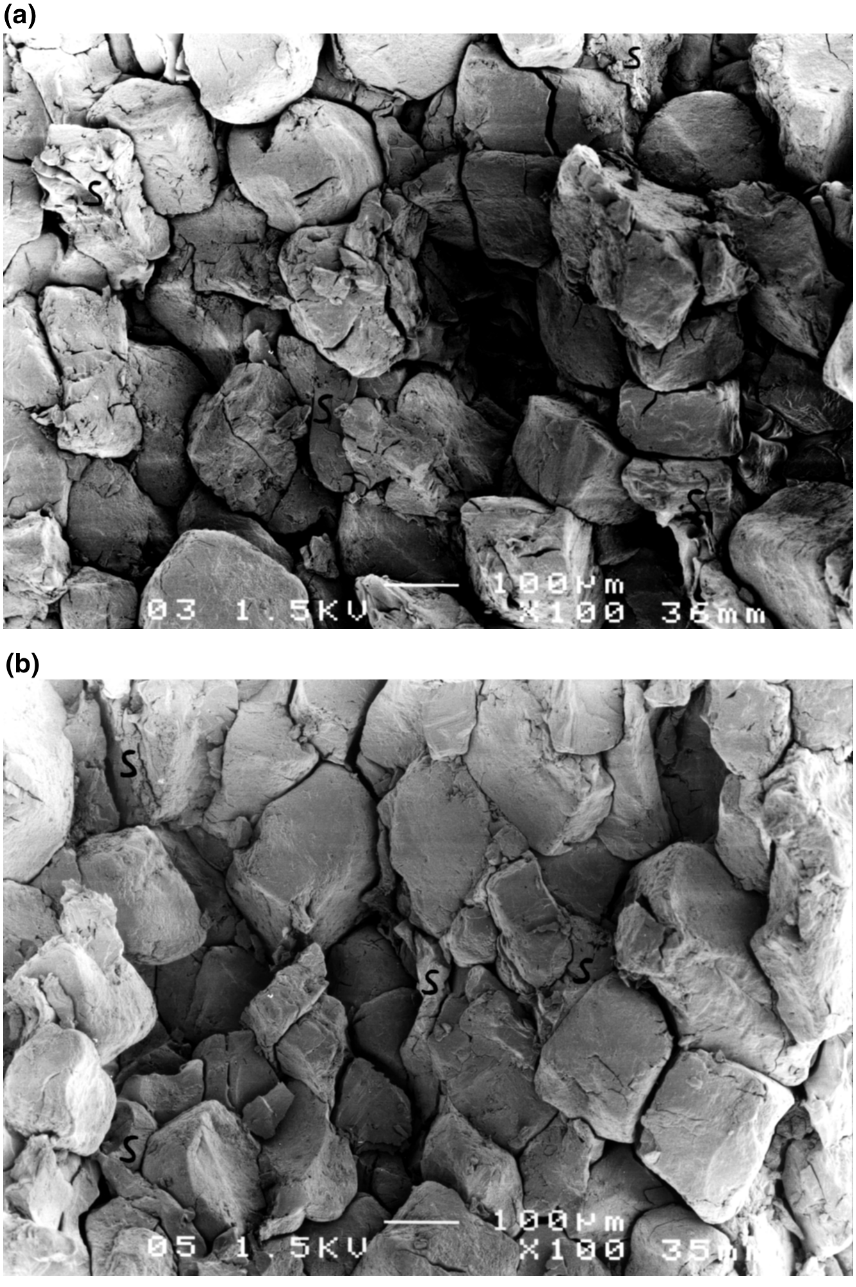

Fig. 2. a: Cross-section of a tablet compressed from a binary mixture of sodium chloride and 10% pregelatinised starch (S, starch particles). b: Cross-section of a tablet compressed from a binary mixture of sodium chloride and 20% pregelatinised starch (S, starch particles). c: Cross-section of a tablet compressed from a binary mixture of sodium chloride and 40% pregelatinised starch (N, sodium chloride particles; S, starch particles).

tinised starch, tablets compressed from sodium chloride show only a small porosity expansion. Fig. 3 also shows that the porosity expansion of tablets compressed from the blends is not linearly related with the volume percentage pregelatinised starch, but shows a sharp increase at low fractions

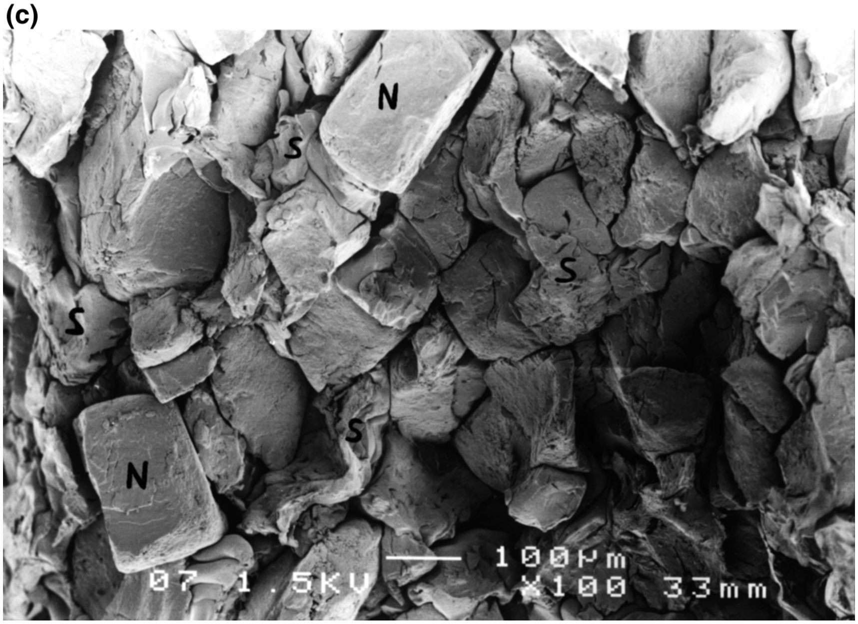

Fig. 2. (*Continued*)

pregelatinised starch. The effect of the addition of pregelatinised starch particles is higher than expected from linear interpolation of the porosity expansion.

Under load, the particles of sodium chloride and pregelatinised starch are closely packed to each other. During tablet relaxation, the tablet volume increases, resulting in an increase in the size and number of pores. The formation of extra pores consequently leads to the formation of more free particle surfaces, which is an effect of partial or complete disconnection of particles. In a tablet compressed from a blend of sodium chloride and pregelatinised starch particles, there are three different types of particle–particle bonding that can, partially or completely, be disconnected:

1. the cohesive bonding between sodium chloride particles;
2. the cohesive bonding between pregelatinised starch particles; and
3. the adhesive bonding between sodium chloride and pregelatinised starch particles.

The SEM-photographs (Fig. 2), especially the one of tablets compressed from the blend of sodium chloride and 40% pregelatinised starch (Fig. 2c), shows that pregelatinised starch particles situated around individual sodium chloride particles have an imprint of the enclosed sodium chloride particles. This implies that pregelatinised starch particles, which were in contact with sodium chloride particles under load, have been detached. This observation is a strong indication for the fact that the adhesion forces between the sodium chloride and pregelatinised starch parti-

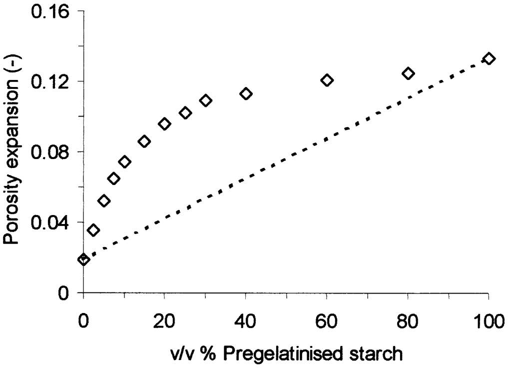

Fig. 3. Porosity expansion of tablets compressed from sodium chloride, pregelatinised starch and their mixtures (symbols) and the porosity expansion calculated by linear interpolation (dotted line).

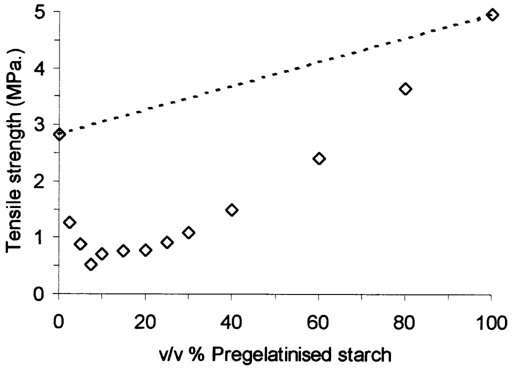

Fig. 4. Tensile strength of tablets compressed from sodium chloride, pregelatinised starch and their mixtures (symbols) and the tensile strengths calculated by linear interpolation (dotted line).

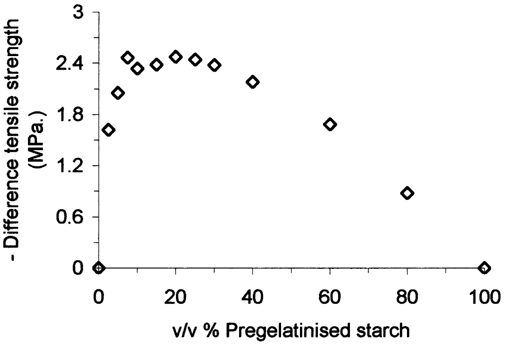

Fig. 5. Difference between the measured tensile strength and calculated tensile strength of tablets compressed from sodium chloride with different volume percentages pregelatinised starch.

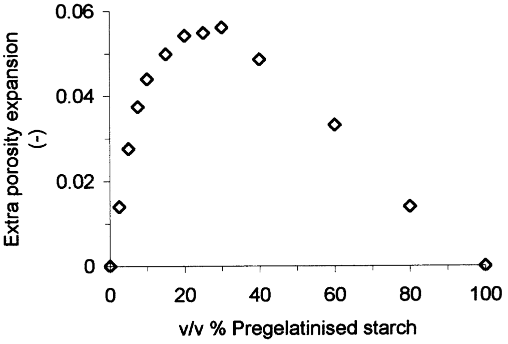

Fig. 6. Extra porosity expansion of tablets compressed from sodium chloride with different volume percentages pregelatinised starch.

cles are smaller than the two different cohesion forces. The observation of smaller adhesion forces can be explained by the fact that sodium chloride and pregelatinised starch have a different type of interparticle bonding (Adolfsson et al., 1999).

3.3. Tablet strength

Fig. 4 shows the tensile strength of tablets with a porosity of 15% compressed from different binary mixtures of sodium chloride and pregelatinised starch as a function of the volume percentage pregelatinised starch. The figure shows that the tensile strength of tablets compressed from 100% pregelatinised starch is higher than that of tablets containing 100% sodium chloride. This indicates larger cohesive forces between pregelatinised starch particles as compared to sodium chloride particles. Furthermore, lower tensile strengths, as compared to interpolation, are found for the mixtures tested.

Strength reduction can be considered as the result of reduction in interparticle bonding. In line with our conclusions from the SEM-photographs, the decreased tensile strength of tablets compressed from the blends indicates that the adhesive forces between the sodium chloride particles and the pregelatinised starch particles are smaller than the cohesive forces between particles of the pure materials. The reduction of interparticle bonding inside tablets compressed from different volume percentages sodium chloride and pregelatinised starch is reflected in Fig. 5 as the difference between the measured tensile strength and the calculated tensile strength (dotted line, Fig. 4).

A decreased tensile strength, caused by a reduction of interparticle bonding, is related to a larger relaxation of the tablets (Rees and Tsardaka, 1994; Van der Voort Maarschalk et al., 1996b; Zuurman et al., 1999). Therefore, the extra porosity expansion between the measured porosity expansion and the porosity calculated by linear interpolation (Fig. 3) is suggested to be a measure for the reduced interparticle bonding. This extra porosity expansion is depicted in Fig. 6.

Both the decrease of the tensile strength of tablets compressed from sodium chloride and pregelatinised starch (Fig. 5) and the extra porosity expansion (Fig. 6) are a reflection of the reduced interparticle bonding inside the tablets. Comparison of the figures, shows that an almost similar relationship was found between the decrease of the tensile strength and the percentage pregelatinised starch on the one hand and the extra porosity expansion of the tablets and the percentage pregelatinised starch on the other hand. The Figs. 5 and 6 have been combined into Fig. 7. This figure indeed suggests such an interrelation of extra porosity expansion, reduced interparticle bonding and the decrease of the tensile strength.

In conclusion, the yield pressures of the blends of sodium chloride with different percentages pregelatinised starch can be calculated by linear interpolation of the yield pressures of the two single materials. The porosity expansion of tablets compressed from the blends is higher than calculated from linear interpolation of the porosity expansion of tablets compressed from the pure materials. Both the extra porosity expansion and the decrease in tensile strength of the tablets compressed from the binary blends are related and caused by a reduction of the interparticle bonding. When knowing the interparticle bonding reduction, caused by adhesion forces that are lower than the cohesion forces, it is possible to predict the relaxation behaviour of the mixture using the properties of the individual components.

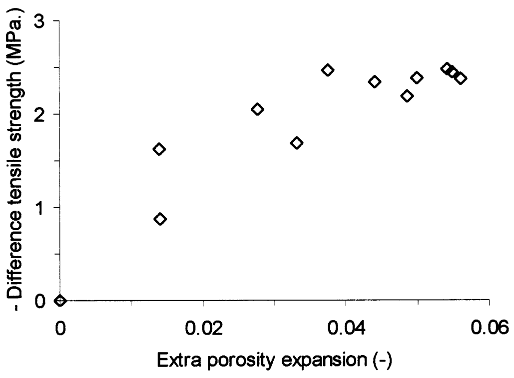

Fig. 7. Difference in tensile strength as a function of the extra porosity expansion.

Nomenclature

k	constant, bonding capacity
P_y	yield pressure
$P_{y,mix}$	yield pressure of binary mixture
P_{NaCl}	yield pressure of sodium chloride
P_{starch}	yield pressure of pregelatinised starch
S	tensile strength
S_0	tensile strength at zero porosity
ε	porosity
ε_{min}	porosity under load
$\Delta\varepsilon$	porosity expansion
φ_{NaCl}	volume fraction of sodium chloride
φ_{starch}	volume fraction of pregelatinised starch

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