

Recent thoughts on greensand control and mould production

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This critical survey of recent developments affecting sand-mould properties represents a condensed evaluation of various research projects completed at the Foundry Institute of the Technical University of Aachen over recent years. Many single results from these investigations of production problems in foundries are included in this thoughtful outlook on the future of greensand technology.

Higher casting production, shorter sand-cycles, the application of high-pressure moulding, increasing numbers of patterns on plates, modified production conditions, changed processing of greensands, neglect of specific bentonite requirements, inadequate sand control and decreasing interest in greensand testing contribute to moulding problems, with obvious consequences for the quality of castings.

Decreasing interest in sand testing and the ineffectiveness of many present testing procedures aggravate the identification of important changes in sand condition. Detailed examples, correlations and conclusions presented in the paper will focus increased attention on the great importance of the condition of moulding material for casting quality and the significance of selected, production-adapted sand-testing instruments and know-how.

Introduction

The change-over of greensand foundries into highly-effective casting production units with increasing application of mechanical and plant engineering is followed by an increasing ignorance of the special requirements of the bentonites as moulding sand binders. Casting quality inevitably requires adequate mould quality. This survey presents production-related examples of recent and significant deterioration in mould quality.

Quality decrease cannot be detected in the short-term. Long-term sand and mould deteriorations proceed very slowly and inconspicuously. Alterations of process parameters and the use of new or modified foundry machinery like high pressure moulding systems may conceal harmful developments. Mould deteriorations are hardly detectable with conventional sand testing procedures.

Present sand testing needs profound revision. The green compression-strength, measured with the 3-ram test specimen, remains after 60 years of unchanged application one of the fundamental test principles. It is more likely to be misleading than helpful according to present production conditions. This research paper reports on new and more informative testing equipment as well as a more useful application of conventional instruments.

Major attention is paid to the adaption of laboratory testing to the actual shop-floor foundry conditions in order to gain more reliable results for quality assurance of casting production. Sturdy pressure gauges are proving to be simple instruments for linking laboratory test results with the mould properties at production lines. The influence of sand compaction is of major significance and its effect on property changes has to be considered.

Major spring-back in the age of high-pressure moulding is of increasing importance. Its detrimental influence on major mould properties unfortunately cannot be detected with conventional testing procedures. Test results have to be evaluated differently and as a result of increasing compaction. Quality assurance ought to consider simultaneous alterations of pairs of property values in control diagrams like the strength-net-chart and micrometer diagram. They offer unique possibilities to supervise spring-back influence and mould brittleness, which obviously increasingly aggravate moulding problems.

Higher rates of casting production with less moulding sand, shorter sand cycles, shorter mulling time, use of under-powered mullors, lower temper point water content and increasing amounts of core sand count for higher mould brittleness and increasing danger of 'over-compaction'. A considerable, latent, and therefore useless strength potential is concealed in many of the present production sands. Mould brittleness unfortunately is additionally aggravated by high-pressure moulding, which is identified by measurements with the moulding sand micrometer. Evaluations of the influence of compaction intensity have to take into consideration the 'effective compaction pressure' inside sand moulds, which in many cases exceeds the compaction pressure of the moulding machine many times.

The loss of bonding properties in present production system sands results in higher demands for active clay. A continuing and increasing trend has been identified for more active clay. This, again, may reduce mould quality because of further requirements for more effective sand preparation, which cannot be met. Moreover, higher active clay means higher fines content with harmful effects on casting finish.

Sand control cannot be guaranteed by retaining adequate greensand properties alone. Production problems may originate from chemical and physico-chemical influences, which do not impair green-strengths. Severe bentonite degeneration is characterised by decreasing wet-strength due to 'harmful' electrolytes from water additions, sulphur from coaldusts, catalysts from resinous core binders, lignine from wood flours and others. Important examples are cited in this paper.

This survey as a whole points to an increasing danger derived from worsening mould production conditions and should motivate foundrymen to focus increased attention to the harmed situation of moulding sand binders and, thus, mould and casting quality.

MOULD QUALITY CONTROLS CASTING QUALITY

The future of the foundry industry in countries with high labour costs will depend to a great extent upon their ability to produce high quality castings. Casting quality necessitates sound products with excellent finish and predetermined material properties. Casting quality likewise demands appropriate production methods, dimensional accuracy and uniform distribution of properties in all cross-sections of castings. Wall thickness must be reduced in order to reduce weight. Casting quality, however, is adversely affected by advancing casting complexity, which sets increasing standards for mass production.

Aspects of mechanical and plant engineering have increasing influences upon foundry production processes. Moulding materials, however, are increasingly ignored and subjected to new plant demands. Casting quality inevitably requires adequate mould quality. This fundamental demand seems to be increasingly overlooked.

Changes are detected which indicate the deterioration of present production sands with inevitable influence on casting quality in the long-term. They are consequences of increased production, modified production processes and cost savings. Faster sand circulation and shorter mulling times in large sized, inefficient mixers, reduced amounts of circulating

moulding sand, increased sand temperature and higher water demand for sand cooling, contribute to a degeneration of the bentonite binder. The application of high pressure moulding with sands of low temper point water contents and the tendency of increasing yield per mould by increasing the number of patterns result in significant properties being impaired. Table 1 represents quality impairing tendencies in recent greensand technology and their consequences for foundry practice.

DECREASING INTEREST IN SAND TESTING

Decreasing interest in sand testing and neglect of important sand properties are obviously important reasons for unfavourable trends not being detected or appreciated sufficiently by foundry engineers.

'Sand control', according to present interpretation, is mostly restricted to the retention of sand properties during repeated recycling of sand in the foundry. Control processes like 'sand balance' predetermine the amount of sand additives destroyed by the pouring heat and their replacement. But 'sand balance' is no reliable means to detect and prevent serious deterioration in properties, even if the exact quantities of active components in the moulding sand are maintained. Bentonite or coal dust qualities, milling intensity, sand temperature, mould compaction and spring-back, stripping properties, decreasing refractoriness and casting finish due to water-soluble salts and other influences may cause deterioration in casting quality in spite of controlled and unchanged 'sand balance'.

Sand control has to include two different measures: Achievement and retention of optimum sand properties (Table 2). Optimum properties and long-range alterations of the moulding sand have to be explored and supervised by production-adapted, selected sand testing procedures. Only then may 'sand balance' be a valuable part of a predictive control process and be aided by computer systems.

But foundrymen obviously and increasingly have lost interest in sand testing. Sand laboratories are closed, missing, or operated by unskilled personnel.

Some important reasons are the confusing variety of testing equipment available on the market, inadequate experience in the evaluation of test results and disappointing experiences with their usefulness for foundry production.

Misleading compression strength test

One of the main errors of present sand testing is over-emphasis on the significance of the green compression strength which is measured with the 3-ram test specimen. Foundrymen for more than 60 years have used the sand rammer and strength testing equipment nearly unchanged, in spite of the present quality requirements, which set much higher standards. Tradition and simplicity of this testing procedure have contributed to a deplorable stagnation of further sand testing development.

Green compression strength in spite of its predominant application is one of the most misleading sand properties. High values often suggest good sand conditions, which really do not exist. There are many reasons for this.

Many casting defects originate from too-low a green tensile, but not from compressive strength (Fig.1). Even mould-fracture due to sand expansion from the heat of pouring may be a consequence of too-low green tensile strength levels (4b and 5b in Fig.1)

Low tensile strength and associated stripping difficulties in many cases is accompanied by high compression strength values of the same sand. Fig.2 demonstrates a convincing example.²

Three sands with and without 5 and 10 per cent coal-dust additions were repeatedly poured with a heavy grey iron casting. After every cycle 1 per cent bentonite was added in order to maintain compression strength level, this being usual practice in foundry production (Fig.2a). Tensile strength on the contrary decreases sharply with significant results for pattern stripping (Fig.2b). Increasing amounts of coke due to thermal degradation of the coal-dust increases intergranular friction and thus contributes to high compression strength. But tensile strength deteriorates because of binder dilution and decreasing cohesion of the bentonite.

Present laboratory test results do not represent actual mould properties because substantial differences of compaction exist between small 3-ram sand specimens and large production moulds. The green tensile strength tester, therefore, was adapted for measurements at the compacted sand mould itself. It works with a sand specimen (Fig.3a) as well as with moulds on production lines (Fig.3b). Comparison of both measurements result in new findings on sand composition and compaction characteristics.³

Importance of 'effective' compaction pressures

Sand compaction in addition to sand quality decides upon mould and thereby casting quality (Table 2). Compaction quality is not a function of

compaction energy only. Conventional quality control with a 3-ram specimen means a misleading over-simplification and contributes to the decreasing interest in sand testing.

Compaction pressure of the moulding machine according to size, shape and position of patterns splits into higher as well as lower values, which are called 'effective' compaction pressures (Fig.4). A moulding machine squeeze pressure of, for instance 60 N/cm^2 may decrease in the 'shadow areas' to half, but nevertheless may reach triple or even higher effective pressures in 'over-compaction areas'. Strength, spring-back and the danger of mould defects therefore are quite different at different places inside the mould cavity. It is this situation which considerably limits the practical value of 3-ram tests.

Moulding sands differ in 'compaction character'. New sands, because of little energy losses during compaction, are 'highly-compactable' and reach high density and strength with relatively low compaction intensity (Fig.5). Production sands, however, with increasing number of re-cycles develop into 'low-compactable' moulding materials with high compaction intensity necessary to reach sufficient mould properties.⁴ Reasons for compactability decrease are improved bentonite dispersal and sand grain coating, increasing amounts of condensates from lustrous carbon formers and core binders and other influences. As a consequence, moulding machines with low compaction potential work better with high compactable sands (a in Fig.5), whereas sands with higher toughness require higher compaction intensity (b in Fig.5).

Similar requirements ought to be considered in cases of difficult pattern designs. The presence of significant 'shadow areas' as indicated in Fig.4 impedes good moulding of such places with low compactable sands, resulting in casting impairments and deteriorated dimensional accuracy. Moulding machines for this reason are frequently equipped with auxiliary systems for improved pre-filling of 'shadow areas' like vacuum- or shoot-prefilling of the flask or 'fluid impact compaction' (Table 2).⁵

Danger of sand-grain fracture

The unavoidable occurrence of high effective compaction pressures in the mould cavity, which may largely exceed the compaction pressure of the moulding machine, accounts for the appearance of fractured sand grains (Fig.6). In consequence surface area, degree of angularity and bentonite demand increase. Splintered silica sand particles reduce plasticity and

intensify brittleness with important consequences for tensile strength and thereby stripping difficulties (Fig.1). The 'critical effective compaction pressure', which marks the beginning of sand grain fracture, decreases with increasing sand angularity (Fig.7).⁶ Sand grain fracture from mechanical reasons weakens the resistance of silica grains to further destruction. In other words if grain fracture has started, it accelerates with subsequent recycling in the moulding process. Foundrymen should realize the usefulness of round sand grains in resisting the beginning of grain fracture.

Pressure gauges - a new sand testing concept

The properties of small laboratory specimens and large production moulds may be linked, if the 'effective' compaction pressures in both cases correspond. They have to be measured at predetermined places inside the mould and can afterwards be adjusted in the small sand test specimen for production related investigations in the sand laboratory.

Simple and sturdy pressure gauges have been developed. A pressure follower presses a steel ball into a test piece of pure lead with known hardness (Fig.8). The diameter of the impression is measured. The effective compaction pressure is easily derived in N/cm^2 from a calibration curve.³

Pressure gauges can be used as the ramming base underneath a sand specimen (Fig.9a) as well as positioned, before filling the flask, at any place on patterns or the pattern plate (Fig.9b). After compaction gauges are taken out, opened and measured. Several pressure gauges may be linked together in order to obtain complete compaction gradients from one single test. Fig.9b shows as an example several gauges in isolated positions and a combined instrument including 8 measuring points for lateral pressure measurements. Complete gradients are obtained which are helpful tools for evaluating sand compaction research in the shadow area of patterns inside the mould cavity.

Results from a joint laboratory-production-test with a certain production sand are plotted in Fig.10. Tests were run with an air impact moulding machine and the usual laboratory sand rammer. The test situation on the pattern plate was relatively 'open' with only little influence of neighbouring patterns, similar to the position of the middle gauge in Fig.9b. This pressure gauge is surrounded by three measuring heads for the simultaneous determination of the green tensile strength according to Fig.3b.

An air pressure of the moulding machine of, for instance, 5 bar, causes an effective compaction pressure on the pattern plate of about 100 N/cm^2 , which equates with a 'ram-equivalence' of 6 rams (Fig.10a). Higher 'ram-equivalences' may be found in larger sand moulds and with sands of higher compactability⁷ (Fig.5) or especially in areas of 'over-compaction' on top of high, bulky patterns (Fig.4). In these positions 10 or 20 'ram-equivalences' often occur.

Examples like these emphasize the disadvantages of investigations with the 3-ram test. Because of this it is necessary to know the lowest and highest existing pressures during mould production in a foundry. The former are responsible for deformation, erosion and penetration defects and poor dimensional accuracy of the castings. The maximum pressures decide the maximum extent of spring-back with its detrimental consequences for mould rigidity. They further decide upon sand grain fracture and the intensity of sand expansion forces generated at the pouring temperature, which influence the scabbing tendency of the mould.⁸ The range between the lowest and the highest effective compaction pressures in a mould indicates the scatter of mould density (Fig.27), which determines the differences of thermal conductivity and thus is responsible for variations in mechanical properties in different cross-sections of the castings.

The fundamental correlation between the effective compaction pressure and green strength, like Fig.10b, is established in the sand laboratory. Strength values, if needed, can be taken from this diagram at any required compaction pressures.

Fig.11 compares the compaction yield as a result of different sand toughness, which influences the loss of energy during compaction.⁷ Sands with different compactabilities were used, as indicated in Fig.5. A straight line of 13 pressure gauges was placed transversally across the pattern plate with no patterns being present. Low compactable sand Nr. 1 yielded an average compaction pressure of about 130 N/cm^2 , but high compactable sand Nr. 4 gave a value of 180 N/cm^2 . The sharp decrease of the pressure curves towards the mould flask corners indicates the strong influence of flask wall friction, which increasingly endangers a firm 'retention' of the mould parcel inside the flask with decreasing effective compaction pressures of production sands.

Intergranular bridge structures deteriorated

The mechanical structure of binder bridges and their physico-chemical effects jointly determine the suitability for foundry moulds. Finely

dispersed and evenly distributed bentonite particles as well as uniformly coated sand grains are prerequisites for compact and plastic binder bridges with favourable strength and plasticity during pattern stripping. Fig.12a represents the ideal structure, though it can not be reached in production sands.

Foundry experience together with detailed sand investigations indicate an increasing deterioration of moulding sands with inevitable consequences for mould and casting quality. Scanning electron microscope photographs reveal increasing deviations from the ideal bentonite distribution like Fig.12a with a striking tendency towards poorly prepared moulding sands similar to Fig.12b. The appearance of the average binder bridges changes from Fig.13a towards Fig.13b.

Reasons for progressive sand deterioration

Moulding sand deterioration is recognized more clearly at higher magnifications. On one hand poorly-coated sand grains exhibit uncovered grain surfaces and porous binder bridges (Fig.14a). On the other hand crumbly lumps of clay join neighbouring sand grains and form inhomogeneous bridges of high brittleness and reduced load bearing capacity (Fig.14b).

Higher casting production at low mould: metal ratios, rapid sand recycling, shorter mulling time, use of under-powered mills, lower temper point water content and increasing amounts of core sand obviously are main reasons for deteriorating sand conditions (Table 1), which is manifested in Figs 12b, 13b, 14a and 14b. Brittleness increases with accompanying bentonite demand. Active clay content increasingly exceeds 10 per cent (Fig.17). Resulting higher fines content influences refractoriness of moulds and casting finish. Increasing amounts of lustrous carbon formers with higher volatile matter are necessary with the consequence of increasing coke formation (Fig.2) and increasing condensation products, thus again increasing the bentonite demand.

Production sands with high amounts of fines necessitate improved and prolonged sand preparation, but increasing casting production demands unfortunately causes the opposite to occur. Therefore foundrymen must be aware of important fundamentals.

Elementary bentonite particles, originally bonded together firmly in clay aggregates, must be separated ('dispersed') during sand preparation and evenly distributed in order to cover sand grains completely (Fig.12a). This process inevitably demands:

- high-powered mullers. Simple mixing leads to homogeneous bentonite distribution and grain coating, but is never sufficient for intensive bentonite particle dispersion. Bentonite lumps are retained (Figs 12b, 13b, 14b).
- longer mulling times. Bentonite dispersion increases with preparation time with great advantages for strength, plasticity and elasticity of moulds (Fig.13a).
- higher water content during mulling. Swelling of bentonite particles assists bentonite dispersal and shortens necessary mulling times considerably.

High pressure moulding unfortunately requires moulding sands with reduced water contents in order to improve the ability of the sand mixture to fill the shadow areas between patterns. Increasing sand riddleness is necessary, if more patterns are placed on the pattern plate and distances decrease. Temper water point before introduction of high pressure moulding was about 50 per cent compactability. Today it amounts in many cases to 40 per cent only or even less. This is one important reason for significant losses of mould quality presently occurring.

Demands for high casting production in future will confront foundrymen increasingly with quality reductions instead of improvements.

Deformation limit

Introduction of high pressure moulding additionally increases mould brittleness and the necessity for special testing instruments. The 'moulding sand micrometer' measures two significant characteristic properties of greensands from the same specimen: deformation limit and shear strength. Fig.15 represents the fundamentals of sand testing.⁹

Deformation limit indicates the ductility of compacted sand moulds until binder bridges break and fracture occurs under the action of shear stresses. Deformation limit only amounts a few tenths of a millimeter but nevertheless decisively influences important moulding properties. It acts on pattern stripping, mould elasticity during compaction, spring-back consequences, core insertion, mould assembly and others.⁹

Deformation limit and shear strength are compared in the 'micrometer diagram' with important significance for foundry use (Fig.16). 'Poor' sands and their detrimental effect with increasing compaction are clearly differentiated by a sharp decrease of the deformation limit (sand A, lower field of curves in Fig.16). Deformation limit, in spite of increasing

strength, exceeds critical values thus indicating high mould brittleness due to high pressure compaction. High mould strength together with low mould deformation limit endanger mould and casting production.

Suitably processed production sands on the contrary indicate nearly double deformation limits at equal or even lower strength level after low or medium compaction (sand B, upper field of curves in Fig.16). The strong strength increase with higher compaction reveals the character of sands with low compactability, which need hard compaction for sufficient strength (Fig.5).

The micrometer diagram demonstrates one of the most serious disadvantages of high pressure moulding. Deformation limit and therefore brittleness of sand moulds deteriorate with increasing compaction. Probable causes have been described.⁹ This deficiency is tolerable for well prepared sands with extensive plasticity, like production sand B in Fig.16, which even at low moisture content still guarantees deformation limits of about 0.3 mm. But one of the most aggravating problems of present greensand technology is the tendency for poor preparation conditions resulting in increasing mould brittleness similar to the low-plastic behaviour of sand A in Fig.16. Sands of that kind at low water contents reveal remarkable strengths, but deformation limits far below the boundary conditions of around 0.15-0.20 mm.

The strong influence of water content on plasticity once again requires well prepared production sands. Only then water losses can be borne without danger. Production sand B, for instance, with 6 rams decreases its deformation limit at 30 per cent compactability to 0.25 mm, but sand A with about 0.1 mm is suitable for very simple castings only. Sufficient shear strength of more than 4 N/cm^2 suggests adequate sand properties. The risk of quality control by strength tests alone is visible once more.

Active clay requirements

The low plasticity of present production sands results in higher demands for active clay. Deformation limit again reveals important correlations. Several foundry sands were tested at different water contents (Fig.17). None of these sands contained any other organic material usually added for higher plasticity. All sands, independently from their active clay content at low water content (approximately 30 per cent compactability), show quite similar deformation limits as low as 0.1-0.2 mm.

The consequences for foundry production are obvious. Apparently most present sands are of a similar low quality preparation standard and

therefore do not reveal any clear effect of high clay contents at low water contents. Only with higher water level (50 per cent compactability) because of swelling of bentonite and thereby improved particle dispersion, an influence of increasing active clay contents can be observed (upper line in Fig.17).

Deformation limits below about 5 per cent active clay surprisingly do not differ at different moisture levels. At 50 per cent compactability they are as low as at 30 per cent compactability (Fig.17). This amount of bentonite obviously is the price which has to be paid for the inadequate preparation quality of present production sands on average. The equivalent of about 5 per cent bentonite seems to remain non-dispersed and inactive, but can be activated by further processing.

Development of reserve bond

Fig.18 reveals the considerable potential hidden in present foundry sands. Two randomly selected sands with different active clay contents were mulled in the sand laboratory for 90 and 180 minutes (so-called 'secondary mulling'). Sand A in Fig.18 started from a poor preparation condition indicated by low deformation limits of 0.15 and 0.35 mm at 30 per cent and 50 per cent compactability. Plasticity during 3 hours of mulling strongly increased up to values as high as 0.35 and 0.75 mm deformation limit respectively. This sand contained 10 per cent clay.

Production sand B with only 7 per cent active clay during the same preparation process was only improved slightly as indicated by the low increase of the deformation limit shown in Fig.18.

The following consequences for foundry production should be noted:

- sand preparation and sand processing requires at least 40 per cent compactability.
- active clay content needs to be above 8 per cent.
- prolonged preparation in sand mullers with good milling ability.

The necessary active clay content may vary considerably according to the required deformation limit and the specific conditions of the foundry concerned (pattern complexity, compaction intensity and homogeneity inside the mould cavity, mould dimensions, bentonite quality, sand additives, core sand contamination and, last but not least, the preparation quality as to the mulling machine, mulling time and water content during mulling).

Beyond this, higher active clay contents are important remedies for

problems and defects attributed to the mould spring-back, which increasingly gains importance in the age of high-pressure moulding.

Over-compaction caused by spring-back

The increase of the packing density in a mould is primarily obtained by plastic deformation of the binder bridges. At high compaction rates, however, the proportion of elastic deformation increases, resulting in more evident spring-back with its detrimental consequences for mould production. Thus spring-back is more evident with high-pressure moulding, no matter whether squeeze, jolt or impulse compaction is applied. Patterns are responsible for strong differences in mould density (Fig.4) followed by corresponding variations in spring-back. Increasing stress gradients inside mould walls impair moulding conditions, enlarging production problems already caused by high mould brittleness.

Spring-back because of the small movement involved can normally not be detected with the naked eye, but nevertheless may cause drastic effects. Binder bridges, in present production sands already brittle and of reduced load bearing capacity, additionally develop planes of weakness (Fig.19b) up to total fracture (Fig.20). Spring-back especially impairs tensile strength with striking consequences for all production stages with preferential action when tensile stresses like pattern stripping and others are involved (Fig.1).

The influences of spring-back is clearly recognizable by measurements of tensile strength but not compressive strength. Tensile load directly stresses planes of weakness (Fig.19b and 21a). Compression load on the contrary compresses and eliminates weak spots (Fig.21b). Compression strength therefore continuously increases with higher compaction energy without any noticeable influence of spring-back (Fig.22a). Tensile strength on the other hand exceeds a maximum value with subsequent decrease due to an increasing extent of spring-back. Decreasing tensile strength beyond its maximum represents the area of 'over-compaction' (dotted curves in Fig.22b).¹

Sand testing has to be operated under production related conditions in order to take spring-back effects into account. Thus, test results demonstrate the extent of deterioration due to spring-back as a consequence of moulding sand composition and compaction. From this reason the green tensile strength tester shown in Fig.3 was constructed in such a

way that planes of weakness and planes of rupture coincide (Fig.23c). On the other hand neither compression nor shear- or split-strength reflect the influences of spring-back, because the planes of rupture of these conventional testing procedures are situated quite differently (Fig.23d and 22a).

Increasing brittleness aggravates spring-back effect

Spring-back can not be avoided, but its harmful consequences may be reduced. Plasticity of the binder bridges is of main importance for reducing the influence of spring-back. On the other hand any procedure increasing brittleness necessarily aggravates mould production problems due to spring-back. Changes occurring in recent greensand technology with increasing brittleness of moulds unfortunately attribute to higher amounts of spring-back as well as more noticeable consequences for mould production. Most important problems to be solved in future sand technology concern plasticity improvements. The moulding sand micrometer and deformation limit may be helpful tools.

Far-reaching effects due to spring-back result from low water contents of moulding sands. Any decrease endangers moulding properties because of the reduction of plasticity. The critical compaction threshold, indicating the beginning of over-compaction, is significantly reduced. According to the laboratory test in Fig.22b this critical value decreases from 18 rams at 3.2 per cent water down to about 6 rams at 2.4 per cent water content.

Thermal decomposition of the bentonite reduces the plasticity of binder bridges and thus is one more reason for increasing danger of over-compaction. Fig.24 demonstrates the influence of temperature on three important types of bentonite of the natural and soda-activated condition.

Calcium-bentonite because of its lower thermal stability, loses strength much below 400 °C with a consequent increase in the liability to over-compaction (Fig.24a). The same bentonite after soda-activation has a markedly higher thermal stability with respect to strength, but nevertheless over-compaction begins very early (Fig.24b). Natural sodium-bentonite from Wyoming (USA) demonstrates its well-known superior thermal behaviour with both properties. This type of bentonite in spite of only medium strength potential maintains strength and plasticity up to about 500 °C (Fig.24c). Even above this relatively high temperature over-compaction does not begin before about 8 rams. Generally, thermal stresses are the main reasons for reduced resistance to over-compaction.

Accumulation of dead-burnt clay in circulating production sands increases brittleness and thus their liability to spring-back consequences.

Recent preventive measures include the use of increasingly high bentonite contents (Fig.28) and the growing use of additions of plastifying organic material (Fig.25). Both measures in the long run obviously are problematic. High bentonite contents tend to cause compaction difficulties and reduced casting finish. As to the long-term application of organic materials, their low temperatures of decomposition and detrimental influence on other sand properties must be taken into account. Additionally many of the organic products offered on the market have limited effectiveness.⁹ Investigations with the moulding sand micrometer are recommended.

The strength-net-chart

The fundamental differences between green compression and green tensile strength, as pointed out in Fig.21a, 21b, 22a, 22b, 23c and 23d, provide the basis for an interesting concept for greensand control. The 'strength net chart' in Fig.26 compares both properties.¹⁰ Straight lines indicate the so-called 'relative green tensile strength'. This value defines the percentage of tensile strength with regard to compression strength at the same compaction level. Line 12, for example, marks all tensile strength values, which amount to 12 per cent of the compression strength.

Green compression strength, which is not affected by spring-back, characterizes the basal binding power of the binder bridges inside compacted sand bodies. Green tensile strength on the contrary is impaired by influences reducing quality, mainly by spring-back effects. A comparison of both strengths at increasing compaction levels therefore renders informations on the amount of spring-back activity. The 'relative green tensile strength' and its alteration with compaction increase is a real standard of value with respect to sand quality and compaction influence.

The ideal increase in both strengths should be proportional, that means linear in the strength-net-chart like the straight line A in Fig.26. But every moulding sand exhibits reductions depending on the amount of spring-back influence. Different strength curves in Fig.26 are discussed in Table 3. Diagram Fig.26 was established by aid of a small pneumatically operated laboratory squeezer,¹ but can equally be evaluated with an increasing number of rams.

The shaded areas in Fig.26 are interpreted with Table 4. They indicate different moulding properties according to foundry experience and range

from area I (totally inadequate) up to the unshaded area with no problems expected at all. This shaded diagram, of course, because of the many specific variables in different foundries is not a quantitative representation for any foundry application, but should be considered as a trend diagram. It enables foundrymen to test substantial changes of the sand character in course of long term mould production.

The strength net chart may advantageously be adapted to specific foundry conditions by use of pressure gauges discussed before (Fig.8). In a first step both strengths are measured by use of a sand specimen made either by squeezing or ramming together with the resulting 'effective compaction pressure' like Fig.9a. Results are plotted in a similar way to Fig.10b. The corresponding strength curve is established in the net chart as a result of the effective pressure, and indications of the number of rams or squeeze pressures are no longer necessary (Fig.27).

In a second step pressure gauges are placed on the pattern layout using the foundry's own moulding machine, to evaluate maximum and minimum actually existing effective compaction pressures (Fig.9b). They embrace this part of the strength curve of the net chart (between points A and B in Fig.27), which is of interest for sand as well as production control. From time-to-time control measurements of strength level and the resulting compaction pressures indicate changes of sand conditions and/or compaction extremes which might endanger mould production. This type of production-related strength net chart allows for variables involving moulding pressure, moulding sand quality, pattern layout etc.

Information on strength potential within greensands is indicated by the amount of strength increase with growing compaction pressure. Sand C, for example, because of high compactability, according to Fig.5, reaches high density with low compaction and no significant increase at higher compaction levels (Fig.26). Low-compactable production sand B on the contrary needs high compaction. Sand D offers remarkable increase of compression strength which remains useless for production because of its weak development of tensile strength. Conditions like this may be deduced from the net chart in order to supervise foundry production.

Bentonite content exerts the main influence on moulding properties. Net chart Fig.28 for Wyoming bentonite quoted as an example proves the necessity for high active clay contents. Only then tensile strength decline may be kept in moderate limits, especially at low water contents (Fig.28a referring to 35 per cent compactibility). Higher water contents result in improved plasticity and thus reduce spring-back influence and straighten strength curves in Fig.28b.

The comparison of Fig.28a and 28b points to one of the main disadvantages caused by the introduction of high pressure moulding. The necessary reduction of the temper water content significantly increases spring-back influence, demonstrated by the increasing decline of the strength curves at lower bentonite level. At 6 per cent, for example, compaction behaviour is insufficient (Fig.28a) and has to be improved by higher contents of active clay up to 8 or even 10 per cent. Thus, the reduced temper point water amount has to be paid with higher bentonite additions. Statistical quality control of many production sands has actually proved that in the years of big sales of high pressure moulding machines a steady increase of the active clay content was reported.¹¹ Present amounts in many cases already exceed 10 per cent (Fig.17).

The strength development of current production sands at low water level is shown in Fig.29. No extreme decline in the curve like F in Fig.26 is observed, obviously because of the high active clay contents in today's production sands. Nevertheless drastic differences are recognized. Several strength curves run adjacent to 10 per cent relative green tensile strength, thus merging into defect area IV in Fig.26. All sands from Fig.29 resemble curve characteristics B, D or E in Fig.26. High strength increase at higher compaction rates indicate in every case low-compactible sands (Fig.5) and necessitate powerful moulding machines.

All sands from Fig.29 show at low compaction level (8 bar) surprisingly similar compression strength values, about 10 N/cm^2 , but different tensile strengths between 0.7 and 1.6 N/cm^2 . This observation again points to the fact that foundry production sands are run according to compression strength with no care for tensile qualities. Tensile strength and relative tensile strength levels in Fig.29 are quite different, thus indicating various qualities for mould production.

When considering the high moulding pressures used for establishing diagrams like Fig.26, 28 and 29, it should not be forgotten that high effective compaction pressures are developed inside sand moulds like Fig.4. Moulding pressure exerted by the moulding machine and resulting 'effective' compaction pressure are quite different.

Greensand retains pollutants

Greensands are blamed for air contamination. Foundrymen at the same time forget the fact that greensand quite effectively filters remarkable amounts of pollutants. The high adsorption power of the bentonite surface

undoubtedly adsorbs high amounts of distillates from core binders and lustrous carbon formers.

Fig.30 represents test results with coldbox core material, which was decomposed by heat and its distillates fed into a greensand test mixture.¹² Precautions were taken in order to avoid high sand temperatures and prevent thermal influences on the bentonite binder itself.

Two peaks of the loss on ignition were found inside the greensand mould. Peak A (Fig.30a) according to SEM-investigations is caused by resin-like condensation products from the resin part and peak B from the solvents of the coldbox binder. Both of them have different distillation and condensation temperatures resulting in the double peak. At more than about 150 millimeter inside the mould wall no increase in loss on ignition was detected. Green-strength does not recover before the end of the second peak B (Fig.30b).

Reduced workplace contamination has to be paid with higher bentonite consumption. The binding power of bentonite particles is greatly weakened by envelopes of organic condensates resulting in substantial strength loss (Fig.30b).

The green-strength - wet-strength transition

'Green-strength' exists only at room temperature. As soon as pouring begins, green-strength changes into warm-strength and finally into wet-strength.

The heat of the cast metal vapourizes moulding sand moisture from the surface layer of the mould cavity. This water vapour condenses in deeper layers, forming different water condensation zones. The 'saturated' condensation zone next to the cast metal suffers highest moisture increase of about 2.5-3.5 per cent, according to the specific heat of the mould components (point E in Fig.31). Next to this layer follows the 'unsaturated' condensation zone with decreasing water contents from point D to B at the border to the unaffected part of the mould with normal greensand properties (point A in Fig.31).

Latent heat, which is evolved on condensation, increases sand temperature up to the boiling point of water. For this reason sand temperature increases from point A at room temperature (20 °C) passing points B, C and D with intermediate temperatures up to 100 °C in the saturated condensation zone at point E. This zone contains the lowest strength in the whole mould cross-section and its properties are critical. It is called 'wet-strength

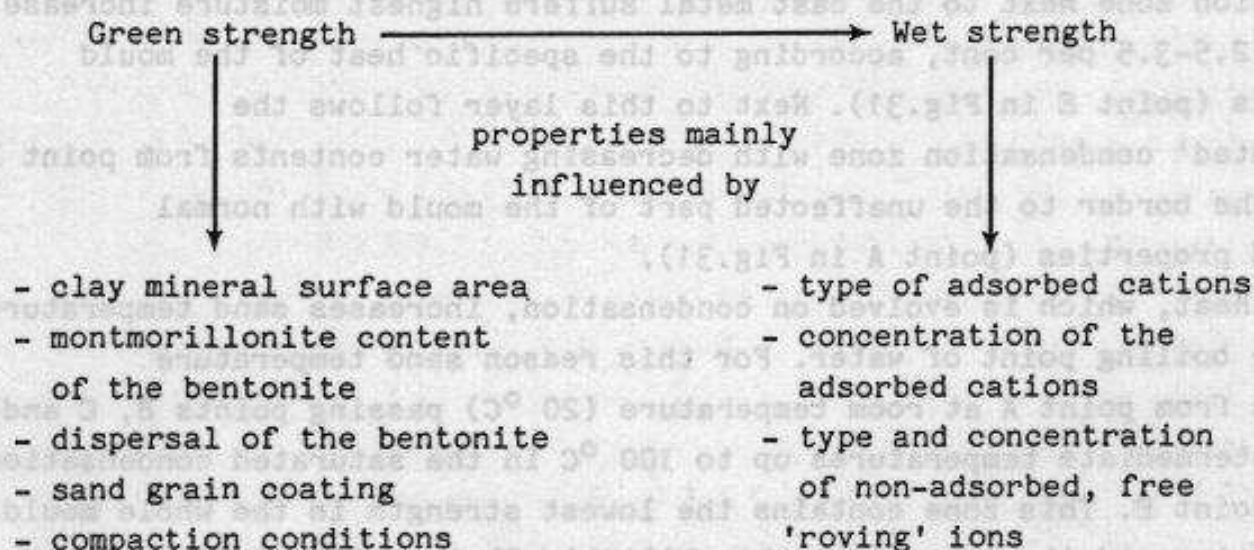
zone'. Between wet-strength (point E) and green-strength (point A) a great number of different 'warm-strengths' are established, some examples indicated by points B, C and D (compare also Fig.33).

Wet-strength, because of its extreme low value and many, sometimes puzzling variables, is of major interest for greensand control and is of great interest for greensand research. The 'wet tensile strength test' was developed in order to simulate the conditions of the condensation zone in a small sand specimen for fast and reproducible measurements (Fig.32).¹³

Increasing temperatures deteriorate the orientation of water dipoles, which are responsible for the bonding capacity between clay mineral particles and, thus, for strength and plasticity. Fig.33, as an example, demonstrates the influence of temperature and moulding sand moisture on strength between room temperature and 100 °C. A steady decrease is found.

Strength curves, according to Fig.33, change their appearance, because increasing temperatures result in changes of the base relationships. The peak of the green-strength, which exists near the temper point of water, disappears. On the other hand, wet strength at 100 °C creates another peak at much higher water contents. Both peaks have different origins. Green-strength mainly depends on the montmorillonite content of the bentonite, wet-strength is determined by the type and concentration of ions present in moulding sands and, thus, is strongly affected by chemical and physico-chemical processes. Detailed reports on bonding mechanism were published.^{13,14,15}

The dotted line in Fig.33 marks the transformation of green-strength to wet-strength due to temperature and moisture increase (A to E). As a consequence the main variables influencing moulding sand properties change in the following way:



Activation of bentonites

Foundrymen frequently limit wet-strength testing to the control and avoidance of sand expansion defects like scabs, rat-tails and others. Wet-strength and compressive forces are basic properties of the 'scabbing diagram'.⁸ This field of application undoubtedly is very useful for foundry production, but is only part of the importance of wet-strength. It really characterizes the latent degree of bentonite contamination, which is not recognizable by green properties at room temperature.

The opposing behaviour of the green- and wet-strengths indicates the fundamental difference between the two kinds of strength. Wet-strength is very sensitive to the many chemical and physico-chemical processes which take place in foundry sands and influence quality of castings. Water soluble salts (electrolytes) exert strong influence on the bonding capacity of bentonites. The fields of force of electrolytes can have advantageous or injurious effects on the electrical bonds which are responsible for the strength of moulding sands. What is the difference between 'useful' and 'harmful' electrolytes?

'Useful' electrolytes intentionally result in an ion exchange with small, univalent cations like Na^+ , which, for example, is obtained by soda additions to calcium bentonites. This process, which results in the formation of sodium bentonite, is called 'activation'. Sodium bentonite guarantees almost the maximum possible wet-strength (point b in Fig.34). Activation quality is controlled by means of the activation curve. The necessary amount of soda addition is indicated by curve section a-b.

Wet-strength is determined by the so-called 'bridge bonding' of water molecules between the individual bentonite particles (Fig.35a).^{14,15} Enclosed in these water-bridges, and of decisive importance for the bond-strength, are the cations adsorbed on the bentonite surfaces. Bridge bonding exists by directed water dipoles within electric fields of opposite polarity. Pre-conditions for this bonding mechanism are high water contents and elevated temperatures in the moisture condensation zone (point E in Fig.33). Green-strength with its quite different bonding conditions therefore shows no reaction to ions present in moulding sands (upper curve in Fig.34). The weak increase of green-strength is due to prolonged preparation time, when soda additions are kneaded stepwise into the moulding sand mixture.

The negatively charged fields of force of the bentonite particles are, however, disturbed and deflected by ions 'roving' around in the bentonite water system. These 'interfering ions' also have their own hydration

shells, which, in the case of anions, are oppositely polarized. In Fig.35b such an interfering field due to a chloride (Cl^-) ion is shown. The water bridges between the bentonite particles are locally weakened or interrupted, so that wet-strength decreases according to the strength and concentration of the electrolyte.

'Over-activation' follows from exceeding soda additions. Carbonate ions (CO_3^{--}) as interfering ions decrease wet-strength (descending part of the activation curve in Fig.34). Sodium bentonites ought to be fully activated by the producer according to point b and should be maintained in system sands as closely as possible.

Present production conditions, unfortunately again, increasingly transfer harmful electrolytes into moulding sands with subsequent bentonite contamination by free, interfering ions. Origins are many: electrolytes from water, sodium-silicate bonded cores, catalysts of the resin core binders, sulphur and chloride contents from coal dusts, lignine from wood flour, the acidity of starch binders and many others. Only a few examples are quoted as illustrations.

Water influences casting finish

Water contains soluble salts and is the cause of an important but mostly ignored deterioration in casting quality, which in most cases proceeds very slowly. Water additions are necessary in order to restore temper water content after pouring and, with increasing frequency, to cool circulating system sands. Water vapourizes, but electrolytes remain and concentrate in the sand.

A single water addition shows no effect. The amount of electrolytes is too small. But with repeated water additions and repeated drying changes are detected. After about 15 additions wet-strength begins to decrease, if strong electrolytes are present (Fig.36). After 80 cycles the bentonite is almost completely degraded. Green-strengths on the contrary demonstrate a tendency towards even better properties. This illusion is obviously due to the increasing dispersal of the bentonite as a consequence of sum total mulling times necessary to homogenize the water additions.

Waters in different foundries are different and contain varying amounts of electrolytes. Sand control necessitates investigations of the water in every individual case, especially in foundries using water for sand cooling.¹⁵

Electrolytes, which are present in many tap waters, are harmful according to the amount dissolved in the water and the solubility of the individual

salts. Fig.37 shows the wet strength decrease with increasing additions.

Harmful electrolytes are identified by a strong decrease in wet-strength. Salts with a water solubility higher than about 10 g/100 g bentonite are distinctly harmful. Where there is a high consumption of water containing considerable amounts of harmful salts in a foundry there is a necessity for water desalinization as a precautionary measure for better casting quality. Casting finish is significantly affected by high concentrations of electrolytes, which decrease the refractoriness of moulding sands. Low wet-strength in the presence of significant amounts of active clay therefore points to the danger of impaired casting surfaces due to sand/metal reactions.

The prejudicial aspects of coal dusts

Increasing demands for improved casting finish on one hand and deteriorating influences on the other focus major interest in the use of lustrous carbon formers like coal dusts. Besides their positive effects they unfortunately show considerable harmful effects. Coal-dusts raise bentonite consumption, increase silt contents of moulding sands and, thus, contribute to casting surface uncleanliness again. Their adverse effectiveness has to be taken into consideration.

Disadvantages originating from coaldusts are not traceable by compression strength measurements (Fig.2a, Fig.38b upper curve). Tensile strength, on the contrary, clearly shows impairing tendencies due to coke formation (Fig.2b, Fig.38b medium curve). Moulding sands are additionally deteriorated by sulphur and chloride released during coal pyrolysis. Bentonite contamination according to Fig.35b is unavoidable.

Pouring tests already mentioned in connection with Fig.2 indicate a strong decrease of wet-strength immediately after the first test casting (Fig.38a).² Comparison between green tensile and wet tensile strength according to Fig.38b points out pronounced differences. The latter decreases about twice as much as the former due to the additional influence of harmful SO_4^{--} and Cl^- anions. The main disadvantage of many coaldusts is their considerable sulphur content, which is oxidized to sulphuric acid in the moulding sand. Fumes originating from coal pyrolysis penetrate the sand voids, reach even remote parts of the mould easily and contaminate the bentonite fast and effectively. Sand additives without volatile matter like graphite on the other hand have no harmful effect, as indicated by Fig.38a. Green- and wet-tensile strength after severe physical and chemical

deterioration finally reach values as low as about 30 per cent of the original strengths.

THE PRESENT SITUATION

The few examples quoted illustrate that many harmful factors are responsible for much lower strength levels in production system sands than would be expected by the actual active clay content. There is no doubt about the fact, that many foundries buy bentonite of suitable quality with optimal activation, but are not in the position to maintain adequate quality during casting production.

Interesting evidence has been obtained from investigations carried out some years ago of many German foundry sands.¹⁵ The average wet tensile strength was confirmed to be 0.18 N/cm^2 . The same report shows that the average amount of active bentonite according to methylene blue tests was 8.3 per cent (Fig.39, middle point). The same addition of fresh bentonite to new sand gives a wet tensile strength twice as high, at about 0.35 N/cm^2 (compare upper curve in Fig.39). This result means that production conditions deteriorate the activation properties of bentonites down to an average of about 50 per cent.

In a salt-free environment a fresh bentonite develops a very strong wet-bond (Fig.35a). The wet-strength rises rapidly with increasing amounts of bentonite (Fig.39, upper curve). It is relatively easy to increase the strength by making small additions of fresh bentonite.

In foundry sands containing high concentrations of salts this does not occur, or only to a slight effect. Increasing the amount of bentonite has only little effect if strong electrolytes are present (Fig.39, lower curve). The fresh bentonite immediately adsorbs harmful ions from the contaminated bentonite already present and, thus, loses much of its effectiveness.

Foundry experience indicates that wet-strength should not fall below certain critical values, otherwise production difficulties will occur. This critical threshold varies for different foundries according to their specific production conditions. Maintaining this minimum value with increasing 'high salt levels' becomes more and more difficult and requires increasing amounts of bentonites. This is one important reason for the relatively high amounts of active clay and fines present in production sands of today.

This relatively high and increasing demand for active clay is obviously a main reason for severe production problems due to deteriorated moulding

sands, which up to now has been kept in limits. But the risk increases, reinforced by the decreasing quality of bentonite as high-grade deposits become exhausted.

Some other measures are currently taken in foundries to counteract inadequacies in moulding sands. Some foundries still use (or re-use) a double sand-system of facing and backing materials. As will be recalled, the use of facing sands was eliminated with the introduction of high production moulding lines. Prior to that time jolt-compaction was common with sands of higher moisture contents and longer mulling times. Sand capacity was much higher with large hopper capacity to 'mature' moulding sands.

Instead of exploiting the natural plasticity of bentonites, foundrymen today consider organic additives in order to improve sand plasticity and reduce mould brittleness. Sand additives are used increasingly to support a crippled moulding-sand binder.

Scabbing tendency has increased because of higher compaction (high pressure moulding) and decreasing wet-strength. This dangerous development is concealed today by the decrease of temper water content, which reduces the thermal expansion forces in poured moulds.⁸ A sudden moisture rise may lead to an unpleasant surprise.

Poor sand conditions are masked by new or improved foundry machinery. High-pressure moulding strengthens the crippled bentonite bond, but increasingly at the risk of consequences due to mould spring-back. Intricately shaped patterns are drawn with difficulty. The surface condition and taper of patterns become increasingly important. Intricate mould parts are substituted by cores.

Uneven mould compaction, supported by an increasing number of patterns on the pattern plate, impedes the moulding of shadow areas between patterns and the flask wall. Low compaction pressures in these areas are no longer able to develop sufficient properties. Friability, fractures, erosion, penetration and other defects are inevitable.

Surface roughness of castings as a result of under-compacted mould areas or intensified mould-metal reactions are counteracted by intensive treatment in shake-out drums and sophisticated surface cleaning machinery. Red hot castings being ploughed through the moulding sand in order to grind and clean their surfaces, opposes the requirement for moulding sand quality.

These and many other measures may be helpful for the moment. But the quality demands of the future will increasingly compel foundrymen to focus increased attention to the situation of moulding sands.

Selected equipment for testing moulding sands

Testing equipment used for the evaluation of moulding sands discussed in this paper is of the following type:

Type PMB for active clay determination with methylene blue.

Type PFG for green compression strength.

Type PGZ for green tensile strength.

Type PNZ for wet tensile strength.

Type PSV for deformation limit.

Type PMR

PME

PMH

for effective compaction pressures.

All testing instruments are supplied by George Fischer AG, Schaffhausen.

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Table 1 Factors impairing quality in recent greensand technology.

Sand testing

- Unimportant greensand testing techniques applied.

Consequences for foundry practice

- Poor greensand control and little importance for mould and casting defects. Decreasing interest in sand testing.

Sand properties

- Shorter sand cycles,
- shorter mulling times,
- use of inefficient mixers,
- lower temper water contents,
- increasing core sand/
- moulding sand ratio,
- higher sand temperatures,
- increasing use of lustrous carbon formers.

- Reduced bentonite dispersion, inadequate sand-grain coating. Lack of plasticity, increasing sand brittleness. Decreasing green tensile strength. Increasing danger of 'overcompaction' of sand moulds. Decreasing moulding sand tolerances.
- Mould cracking and fracturing during stripping of patterns and pouring due to sand expansion. Mould edge abrasion. Sand inclusions, porosity in castings.
- Increasing active clay demand, higher fines content. Decreasing refractoriness, deteriorated casting finish, burn-on.

- Sand cooling increasingly necessary. More electrolytes from cooling water accumulate in sand. Reduced sintering point, impairment of casting finish. Decreasing wet strength, increasing scabbing tendency.
- Increasing quantities of condensates from core binders and lustrous carbon formers coat bentonite particles and decrease strength.

Mould production

- Increasing mould compaction by high pressure moulding machines.
- Increasing number of patterns on pattern plate. Decreasing distance between patterns and the flask wall.

- More evident spring-back increases danger of mould defects during stripping of patterns, enhanced by brittle sands. Sand grain fracture.
- 'Compaction shadows'. Deficient mould edge strength. Poor retention of mould parcel in flask. Uneven density, strength and thermal conductivity inside mould. Dimensional accuracy and uniform distribution of mechanical properties of castings endangered.

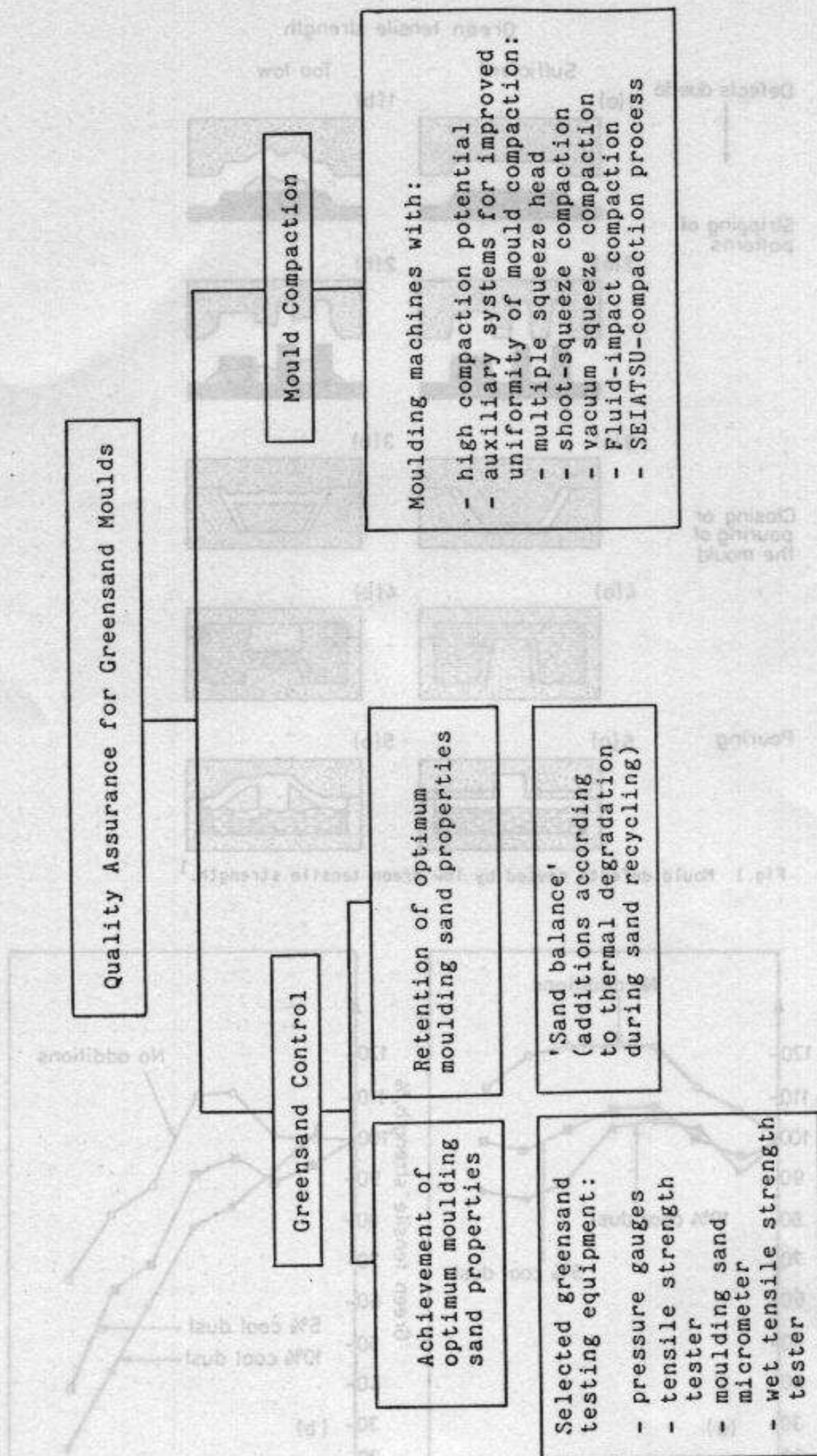
Table 3 Typical possibilities of changing the moulding properties of different sands with increasing moulding pressure.

Curves (see Fig. 26)	Strength variation with increasing moulding pressure		Guide for foundry practice
	Green tensile strength	Green compression strength	
A	Large increase. Increases with compression strength as a percentage of the latter.	Large increase	Desirable ideal condition, but seldom attainable in practice. Desirable very good working conditions attained by planned sand selection. Increasing moulding pressure produces considerable strength gain with no increase in mould defects. Satisfactory working condition. Few or no mould defects. Increasing moulding pressure produces only little increase in strength values, however. Frequent practical condition. Satisfactory working condition at low to medium moulding pressure. However, high moulding pressures augment the typical defects due to mould springback. Frequent practical condition. Sand only applicable to production of simple castings due to stronger tendency to mould defects at all moulding pressures. Good pattern surfaces and high pattern taper require Unsuitable sand with heavy mould defects especially if moulding pressure is increased.
B	Large increase	Large increase	
C	Slight increase	Slight increase	
D	Slight increase	Medium to large increase	
E	Low to medium increase	Medium to large increase	
F	No change to strong decrease	Slight to medium increase	

Table 4 Defect areas of the strength-net-chart.

- Area I: Inadequate moulding properties, severe mould defects. Generally unusable.
- Area II: Inadequate stripping properties. Severe mould defects during stripping are to be expected (edge, corner and mould breakage, mould break-ups, etc.). Frequently even unsuited for simple patterns. Greater pattern taper required.
- Area III: Defects may arise when pressure is released as well as during stripping of pattern from mould. Frequently unsuited for complex sand moulds and isolated heavy mould parts as well as for thin mould cross-sections. Greater pattern taper required.
- Area IV: Defects which are especially likely to result from mould springback (distortion, edge and corner tear-offs, tension cracks in moulds). Care should be taken to ensure sufficient pattern taper and a high degree of surface finish.

Table 2 Greensand control for mould production.



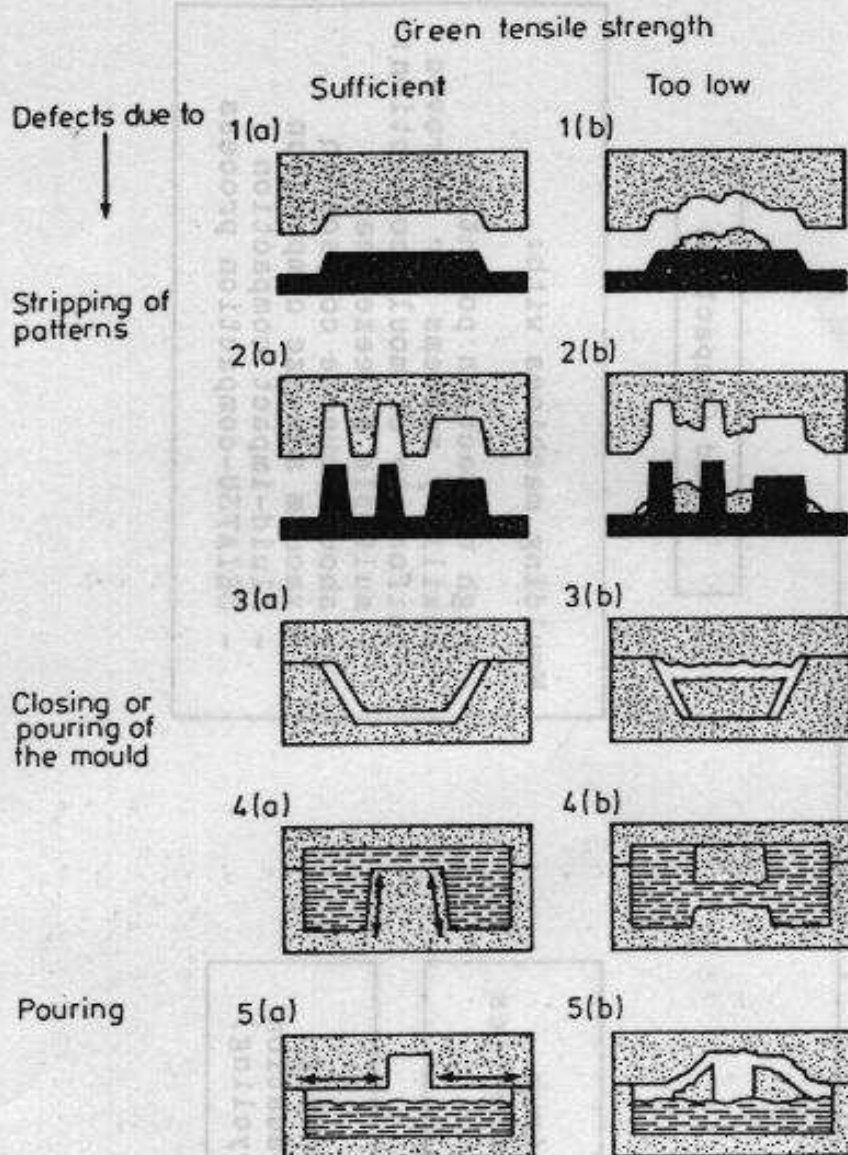


Fig.1 Mould defects caused by low green tensile strength.¹

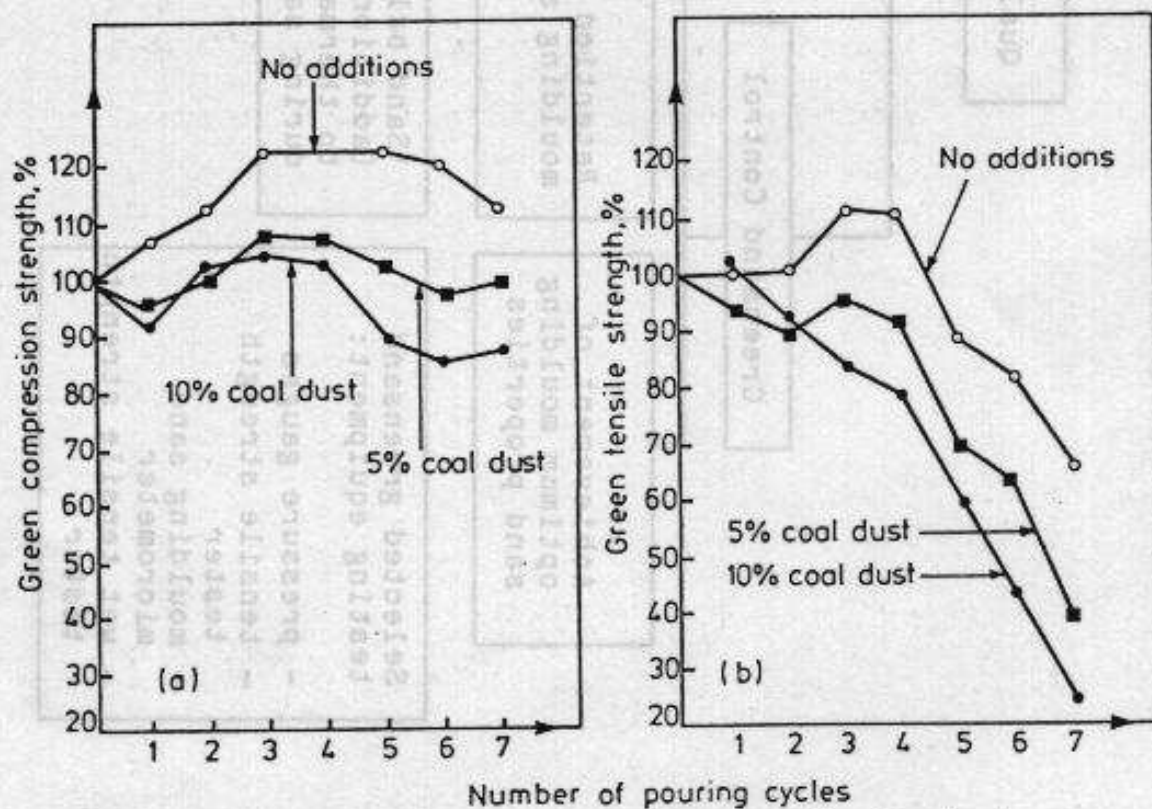


Fig.2 Coal dust decomposition during pouring thermally deteriorates tensile strength, but not green compression strength.²

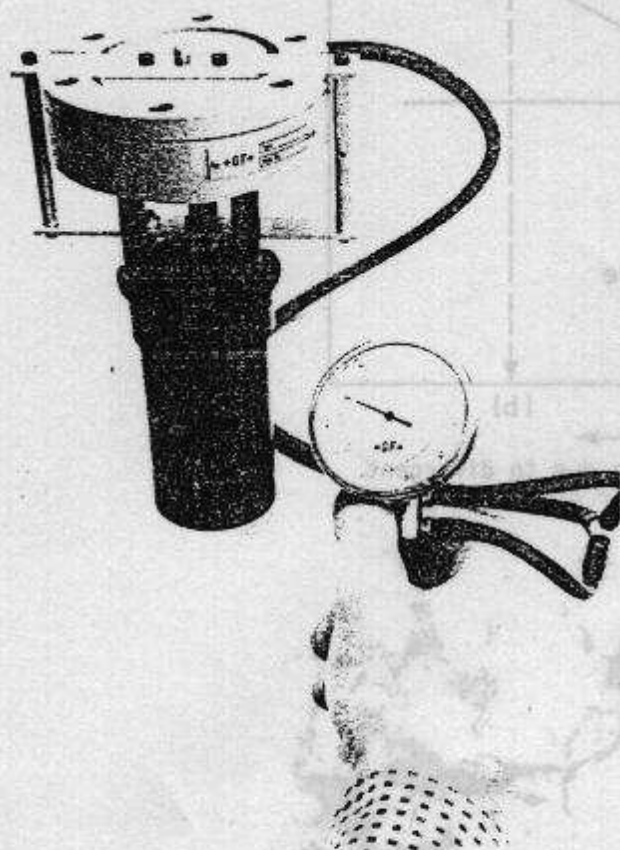
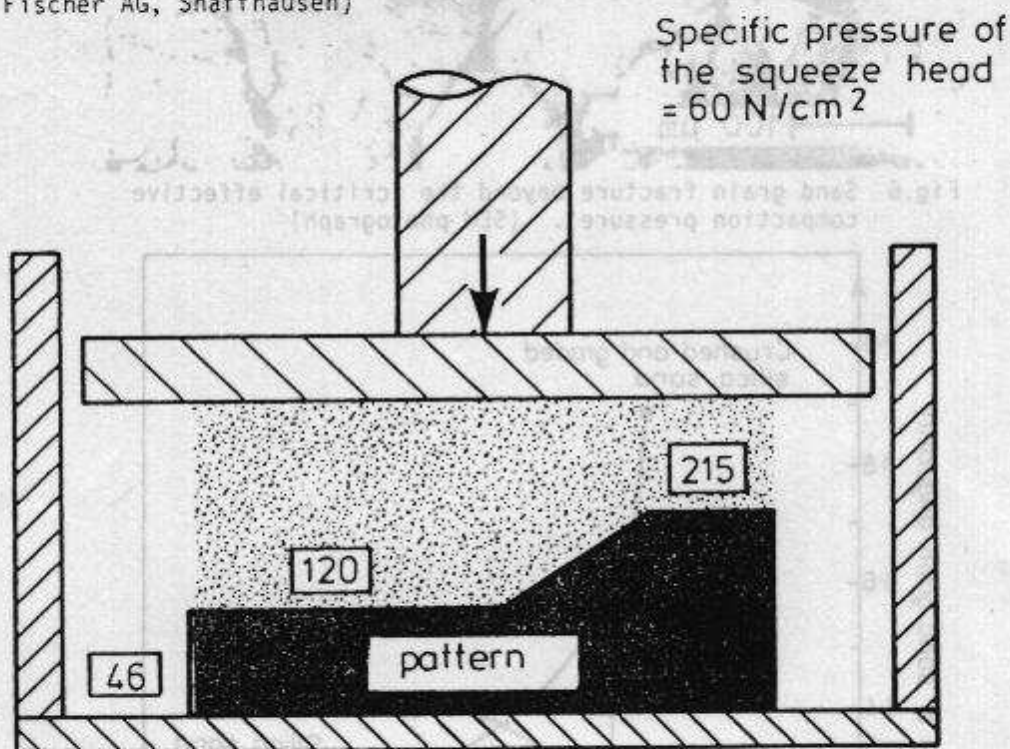


Fig. 3a

Fig. 3b

Fig. 3 Green tensile strength tests with laboratory specimen (3a) and at the moulding line (3b). (Type PGZ testing equipment at Georg Fischer AG, Schaffhausen)



120 = Effective compaction pressure, N/cm^2

= Over-compacted mould areas

Fig. 4 Different 'effective' compaction pressures inside a sand mould due to pattern size and shape.³ (Schematically)

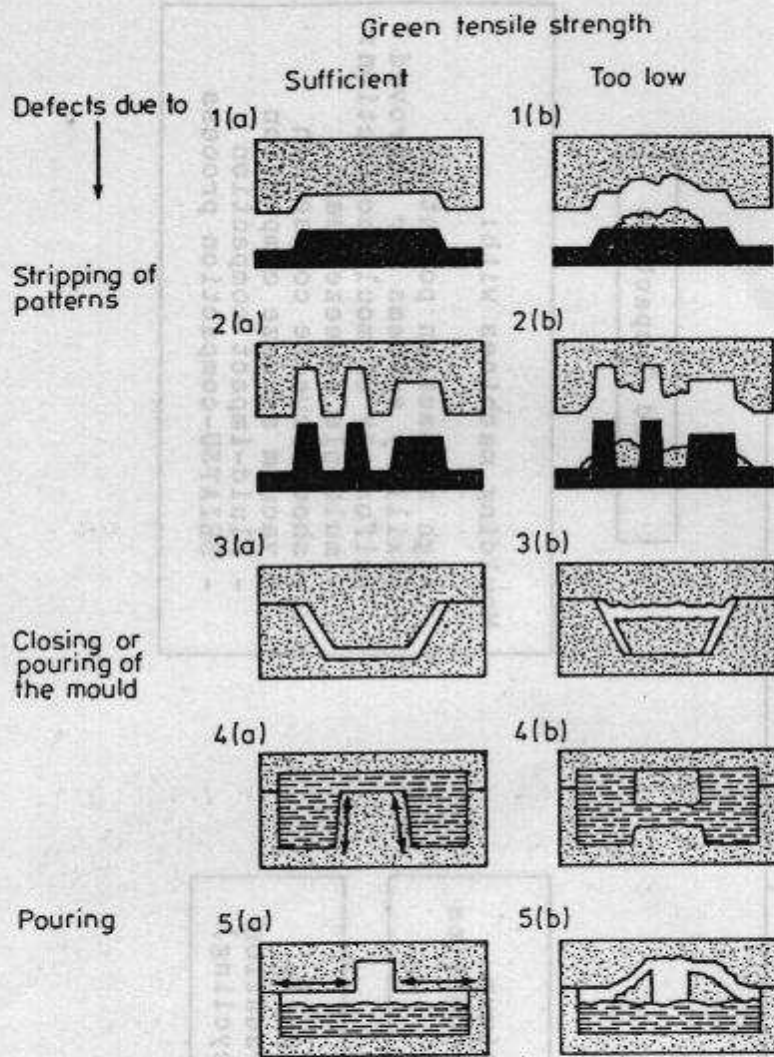


Fig.1 Mould defects caused by low green tensile strength.¹

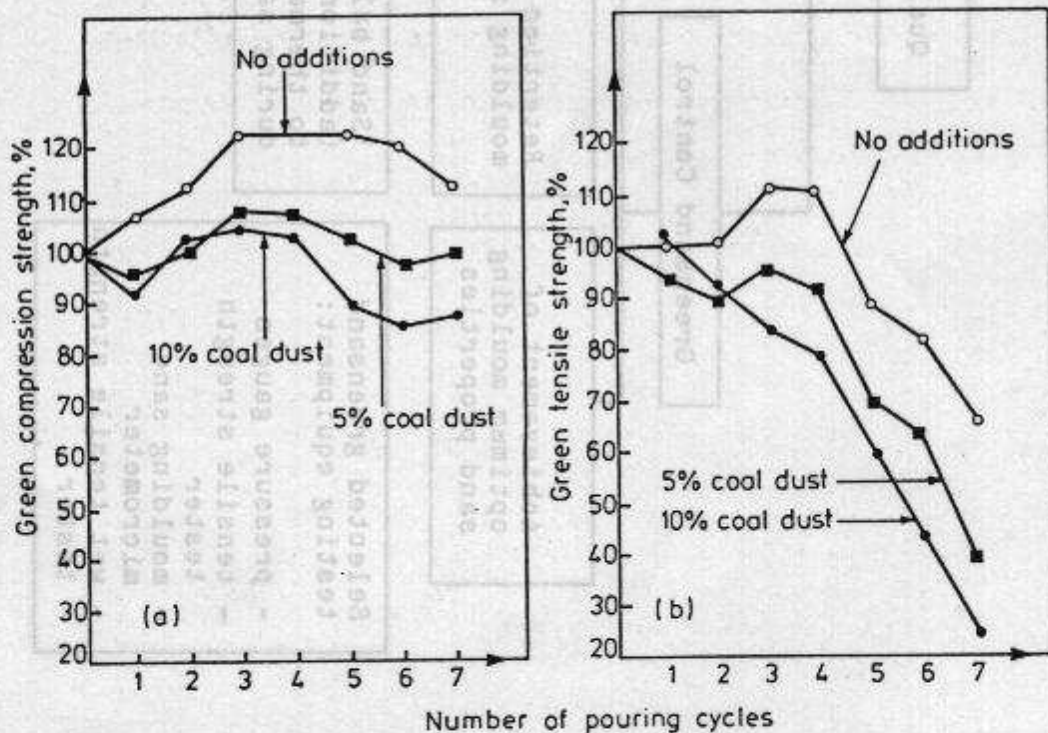


Fig.2 Coal dust decomposition during pouring thermally deteriorates green tensile, but not green compression strength.²
(grey iron castings)

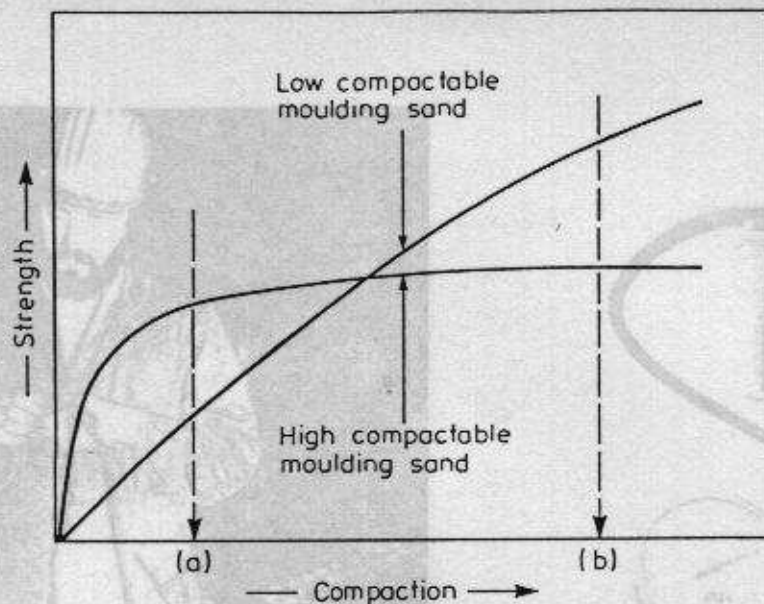


Fig.5 Varying strength increase due to divergent 'compactability' character of moulding sands. (schematically)

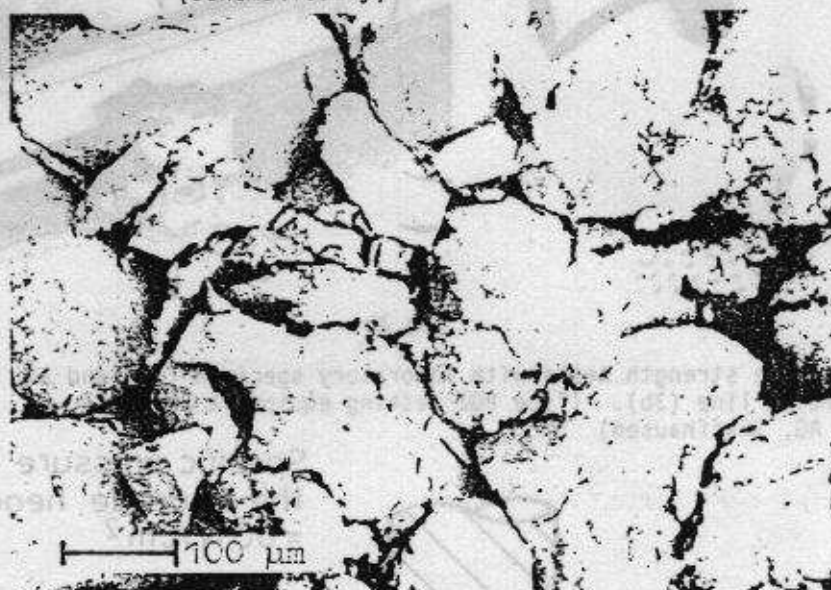


Fig.6 Sand grain fracture beyond the 'critical effective compaction pressure'. (SEM photograph)

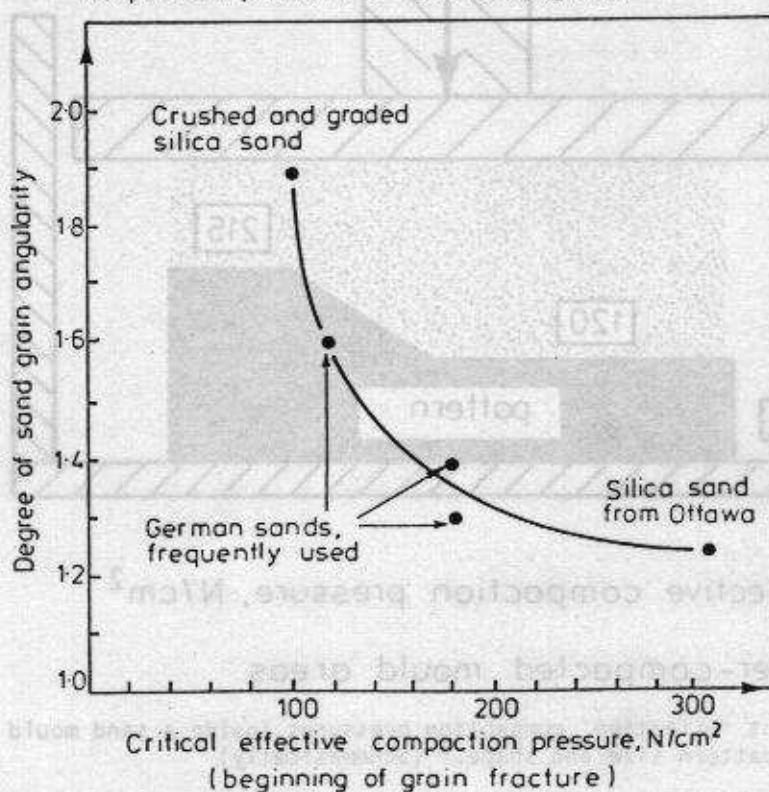


Fig.7 Importance of sand grain angularity for sand grain fracture during high pressure moulding. 6

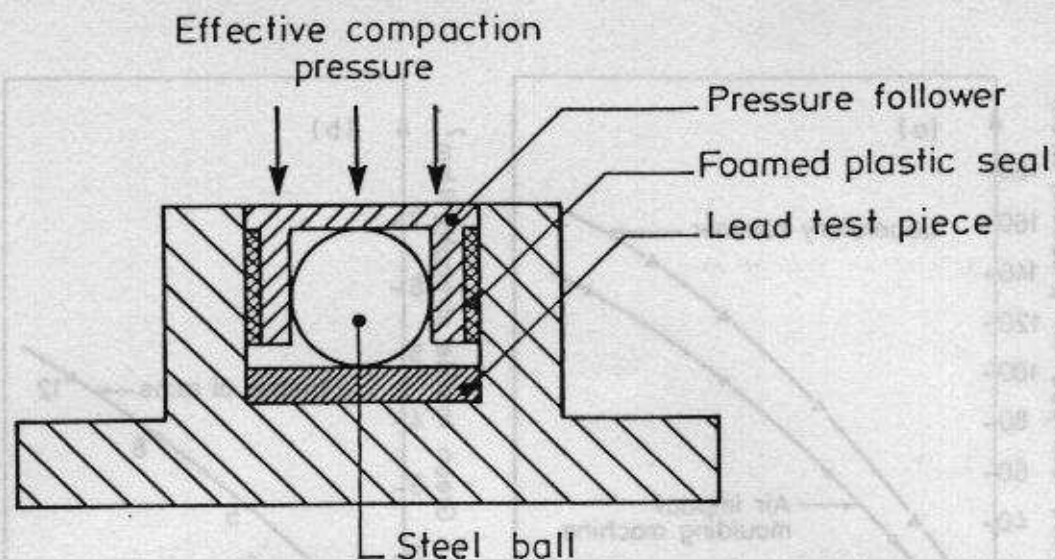


Fig.8 Pressure gauge for measurements of 'effective compaction pressures' inside sand moulds. (Cross-section, Schematically)

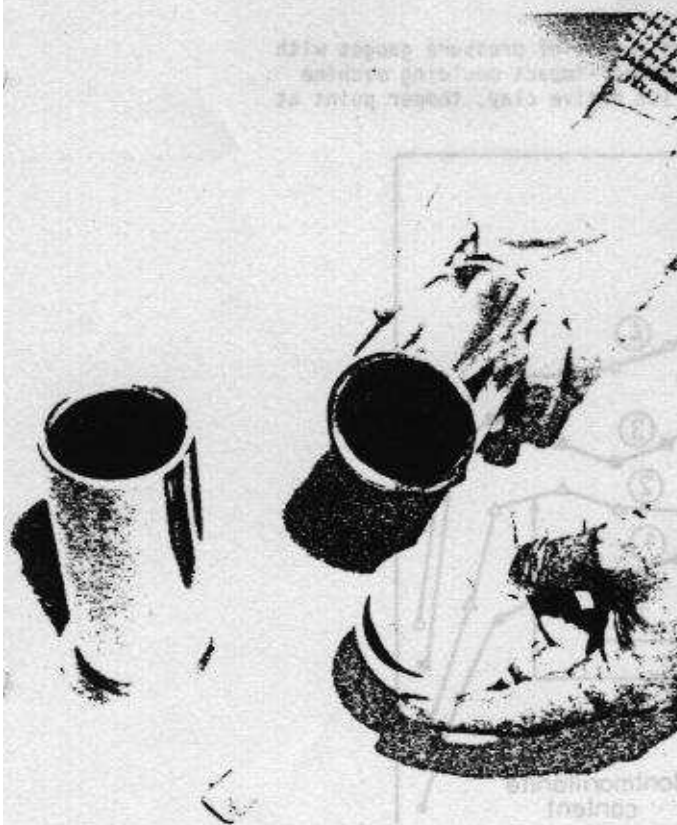


Fig.9a

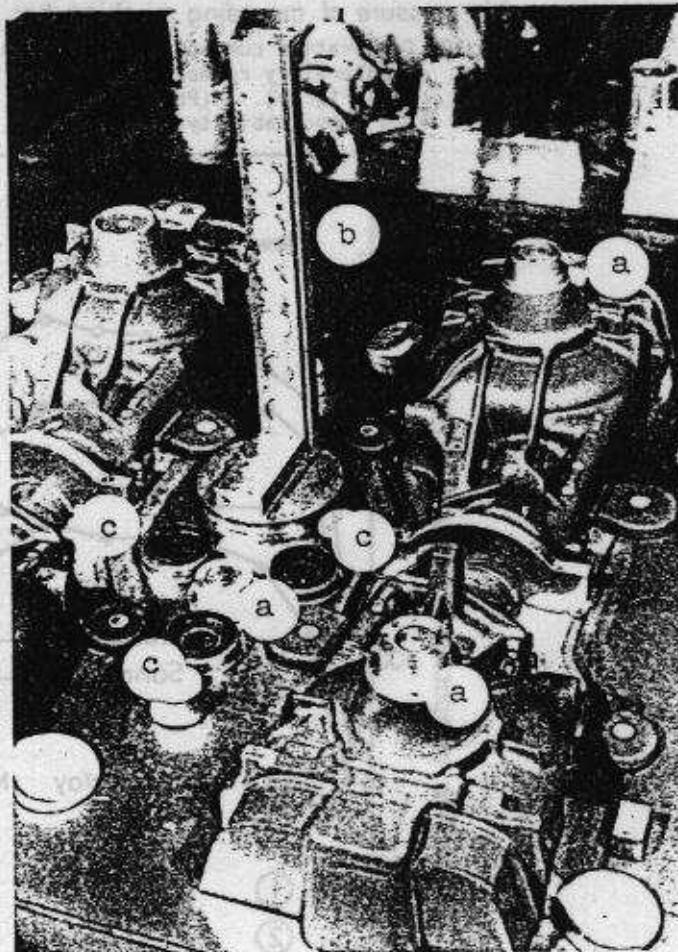
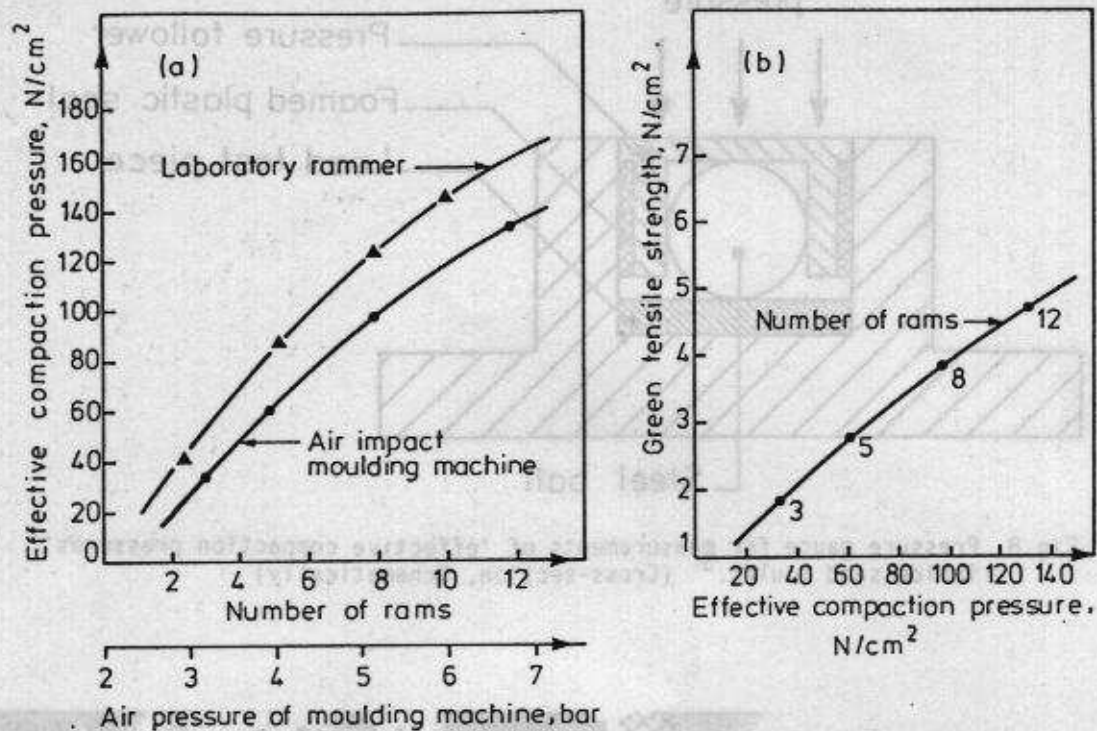


Fig.9b

Fig.9 Pressure gauges applied to laboratory tests (9a) and mould production (9b).

- a = Type PMR pressure gauges in single positions.
 - b = Type PMH pressure gauge combination for complete compaction gradients.
 - c = Type PGZ measuring heads for green tensile strength tests (see Fig.3b)
- (Testing equipment from Georg Fischer AG, Schaffhausen)



Air pressure of moulding machine, bar

Fig.10 Comparative compaction measurements by use of pressure gauges with a laboratory rammer (see Fig.9a) and air-impact moulding machine (see Fig.9b). (Production sand, 10% active clay, temper point at 40% compactability.)

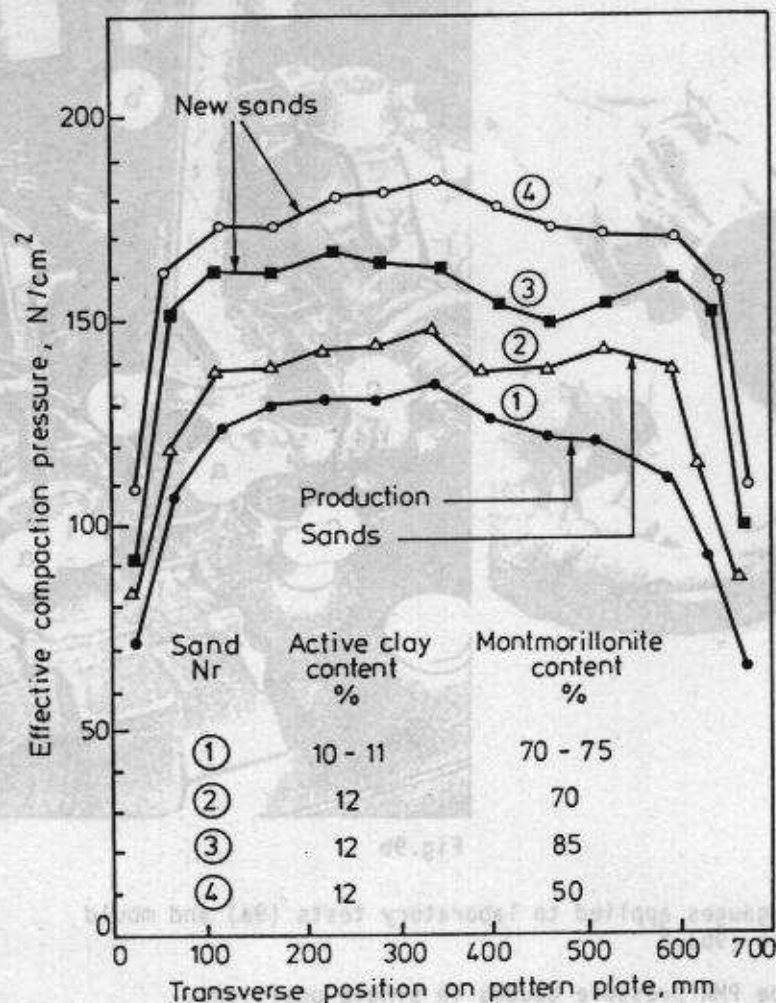


Fig.11 Compaction yield with low- (no.1 and 2) and high-compactable moulding sands (no.3 and 4). (Air-impact moulding machine, 6.5 bar.)

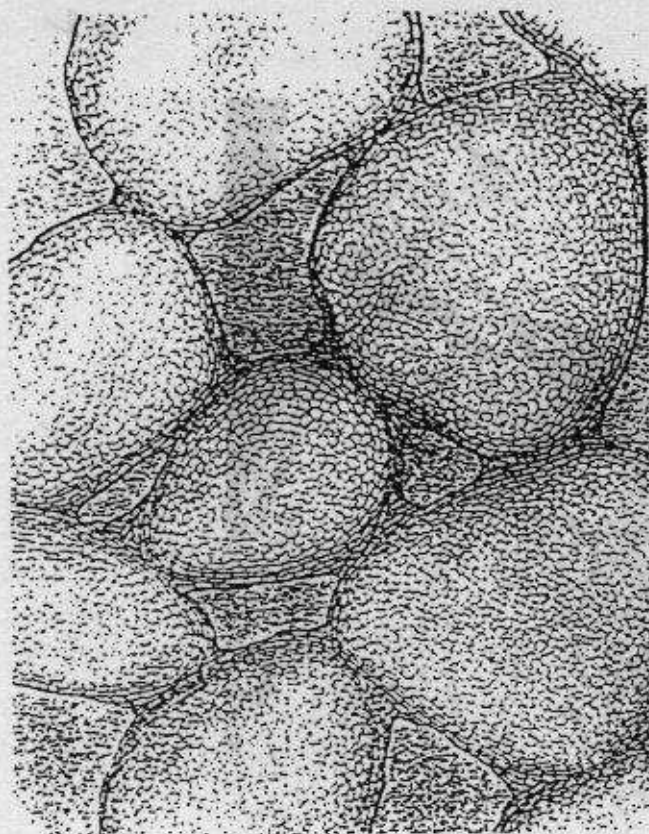


Fig.12a

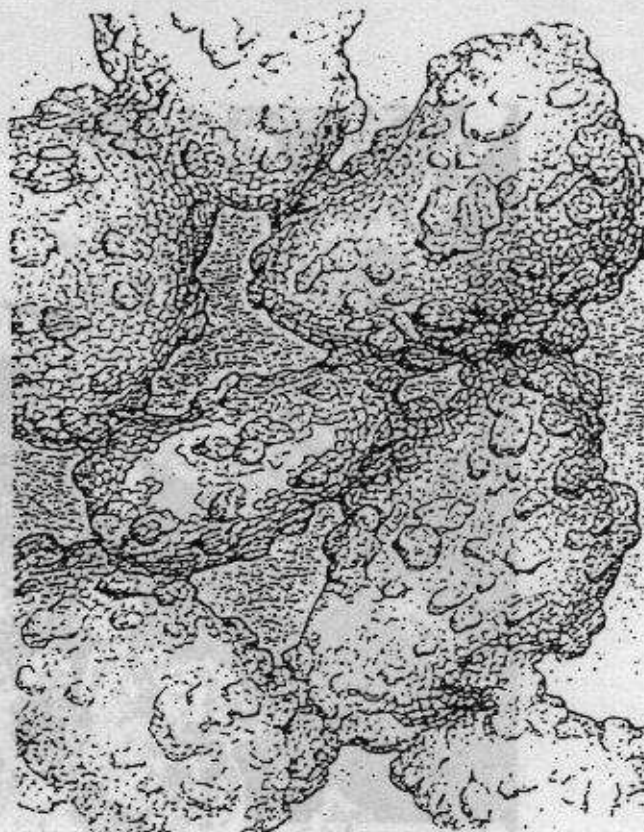


Fig.12b

Fig.12 Ideal (12a) and inadequately processed brittle greensand (12b).
(Schematically)



Fig.13a

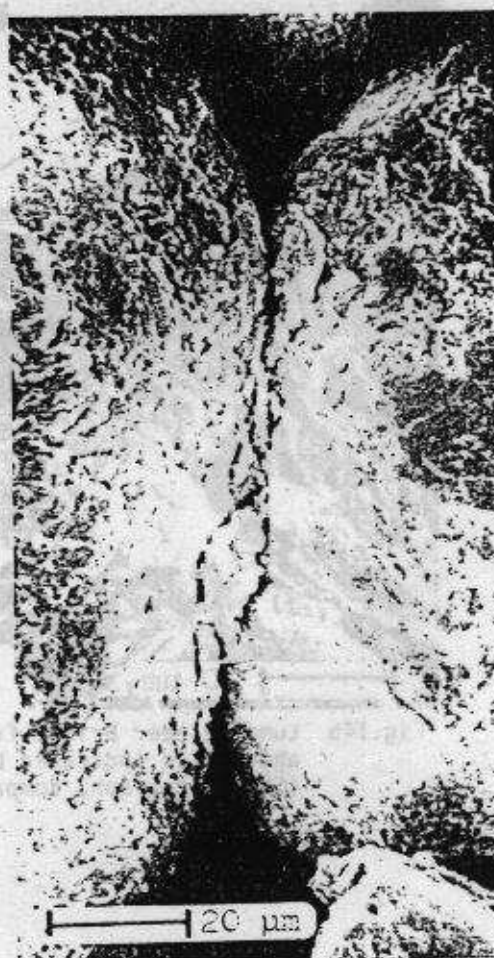


Fig.13b

Fig.13 Well (13a) and poorly structured binder bridge with inadequate
moulding properties (13b)
(SEM photograph; 10% active clay, 3 rams)

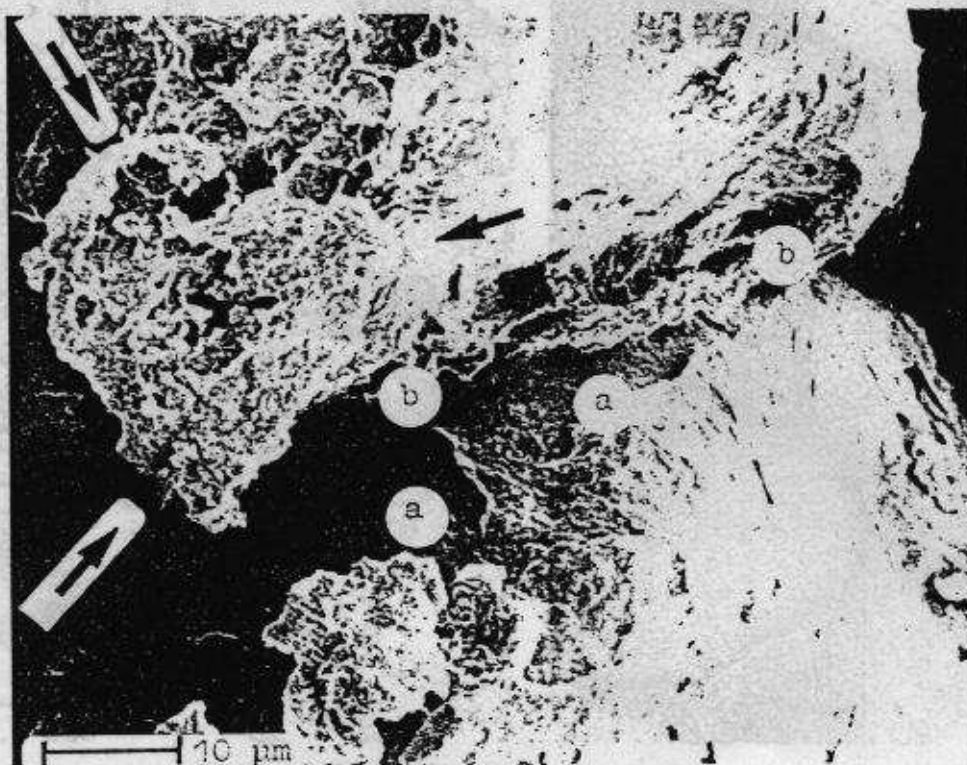


Fig.14a Poorly coated sand grain surface (a), spongy binder bridge (b) and porous bridge abutment (between arrows). (SEM photograph, compare also Fig.12b)

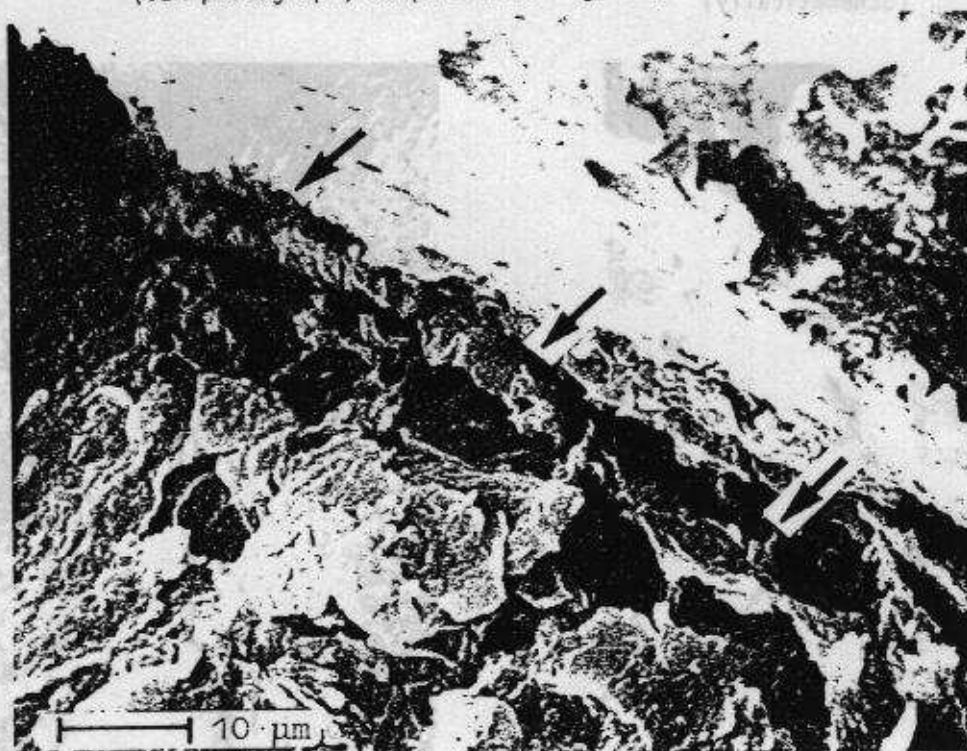


Fig.14b Lumpy binder bridge from inadequately dispersed bentonite aggregates indicated by arrows. (SEM photograph, compare also Fig.12b)

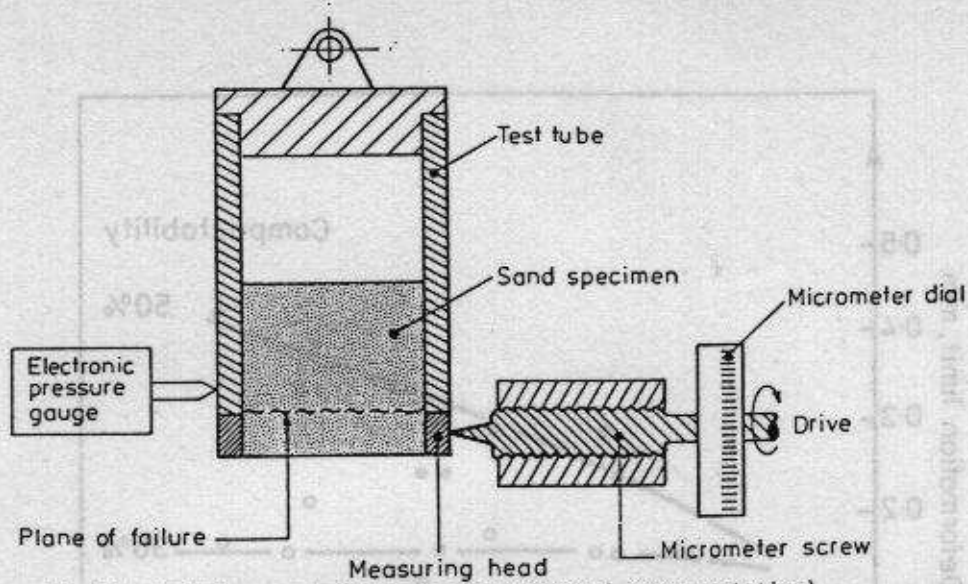


Fig.15 Moulding sand micrometer (schematic representation).
(Type PSV testing equipment of Georg Fischer AG, Schaffhausen)

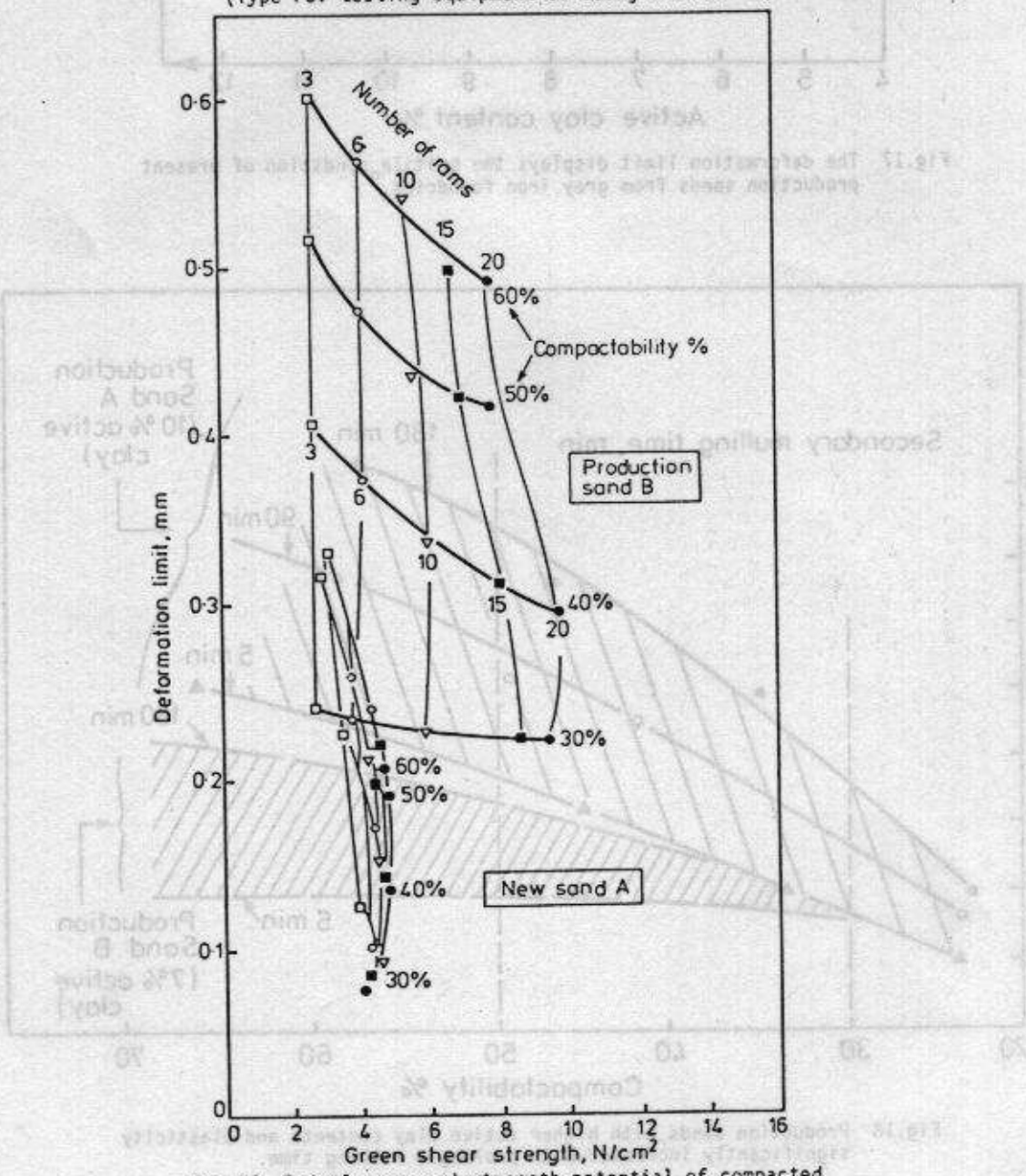


Fig.16 Brittleness and strength potential of compacted moulding sands identified by the 'micrometer diagram'. (Both sands with 10% active clay.)

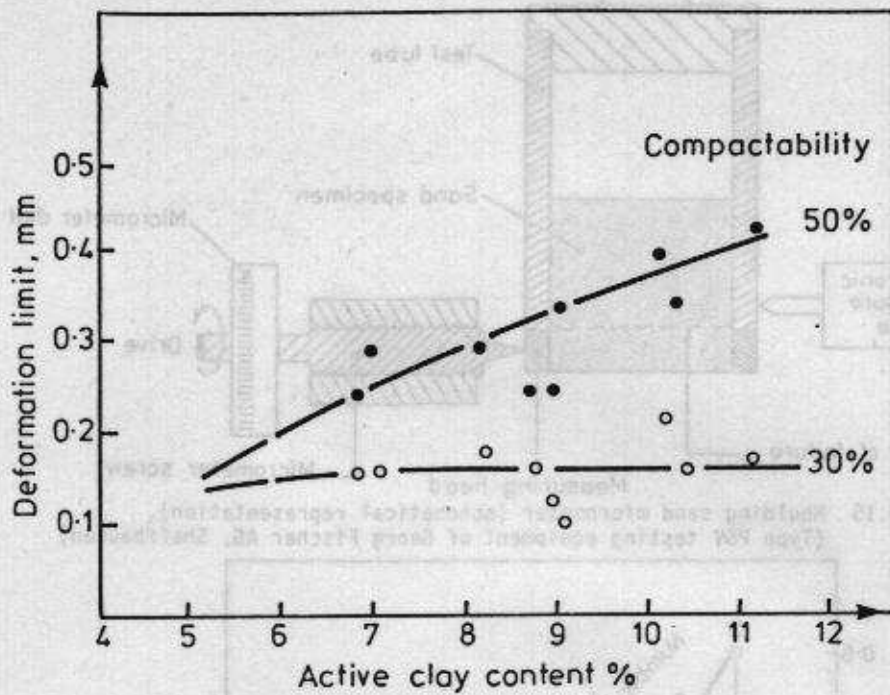


Fig.17 The deformation limit displays the brittle condition of present production sands from grey iron foundries.

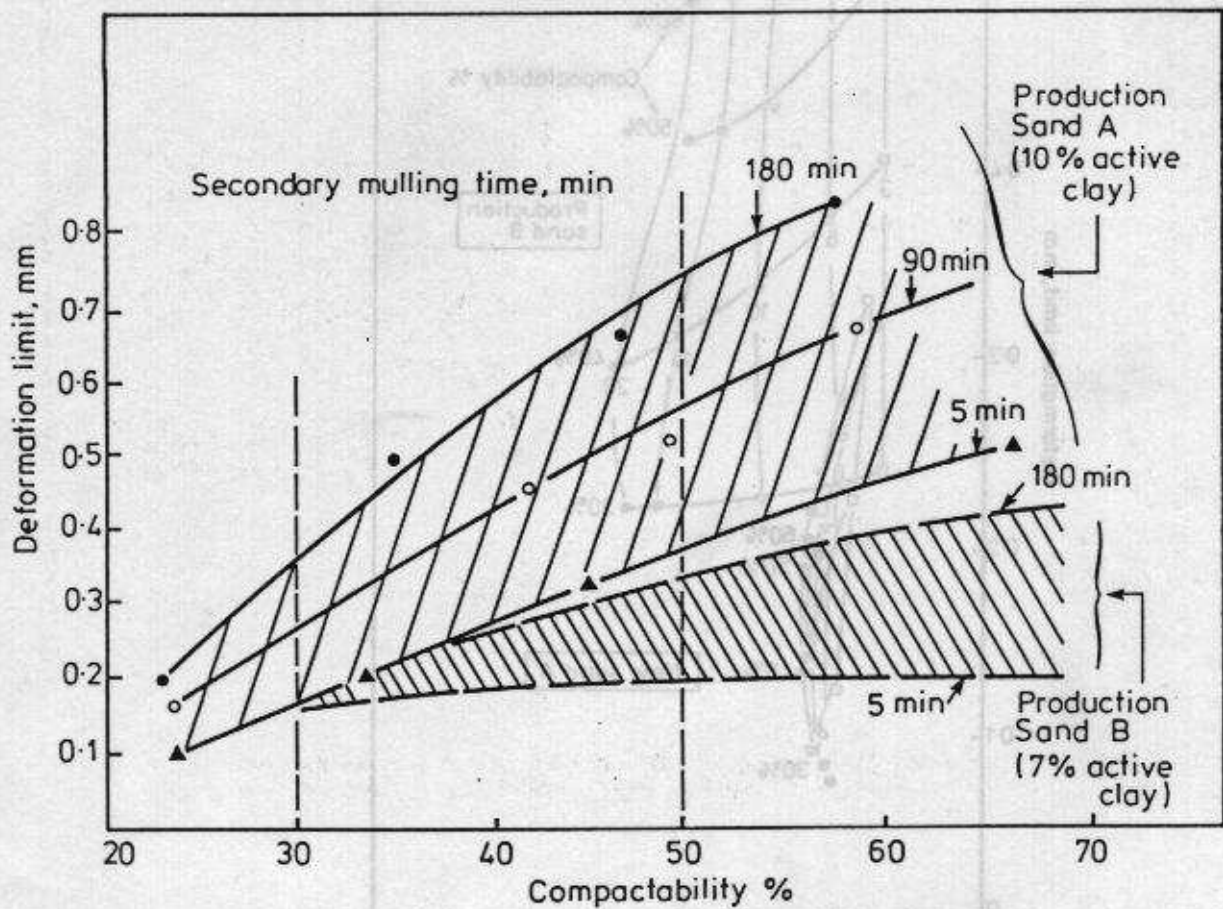


Fig.18 Production sands with higher active clay contents and plasticity significantly increased with prolonged mulling time.

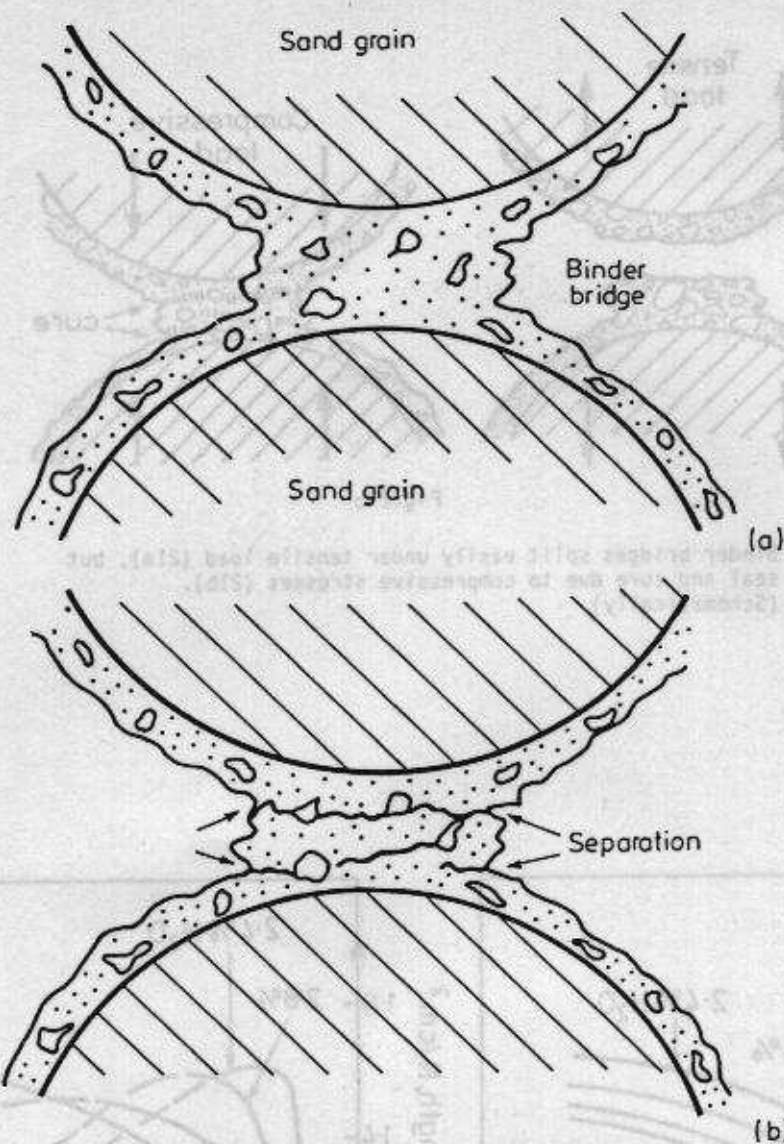


Fig.19 Binder bridges disrupt at higher compaction rates due to spring-back effects (19b). (Schematically)

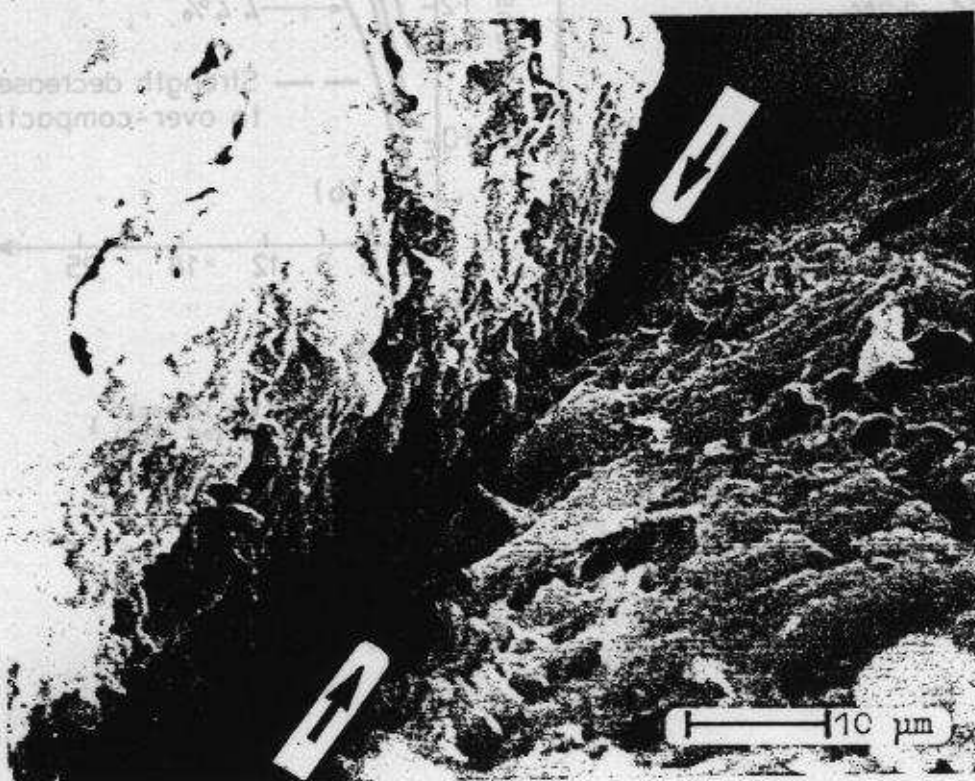


Fig.20 Broken bentonite bridge due to spring-back (between arrows). (SEM photograph)

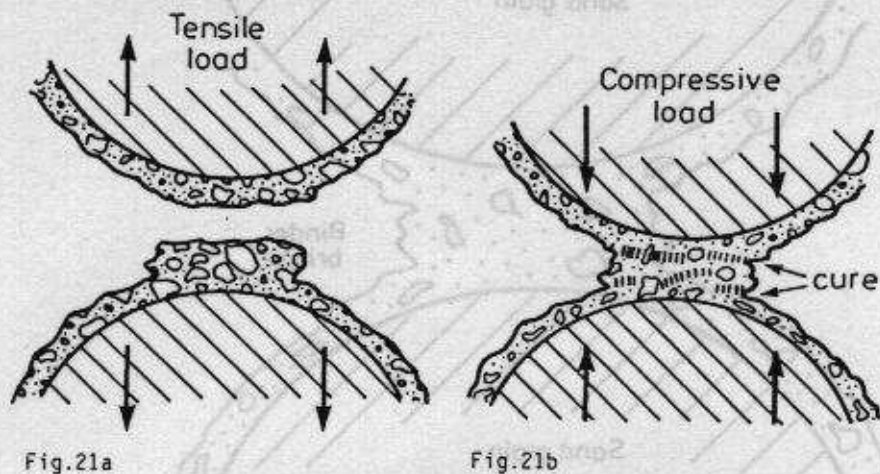


Fig. 21 Binder bridges split easily under tensile load (21a), but seal and cure due to compressive stresses (21b). (Schematically)

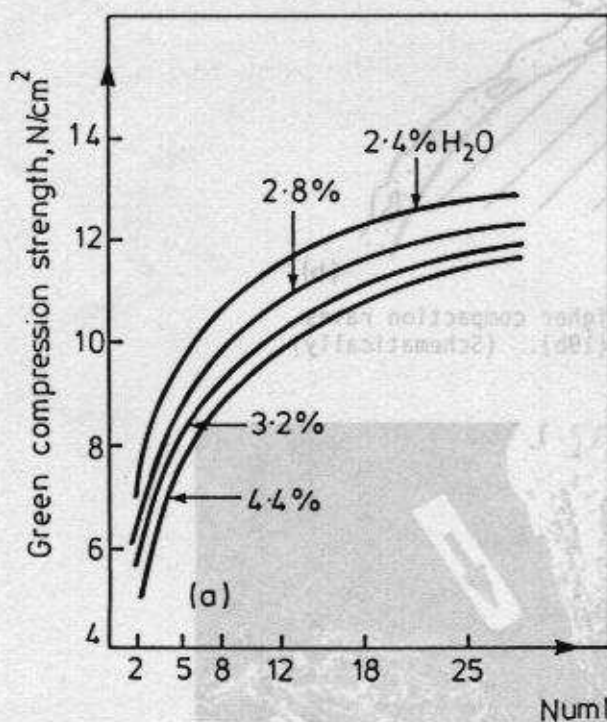


Fig. 22a

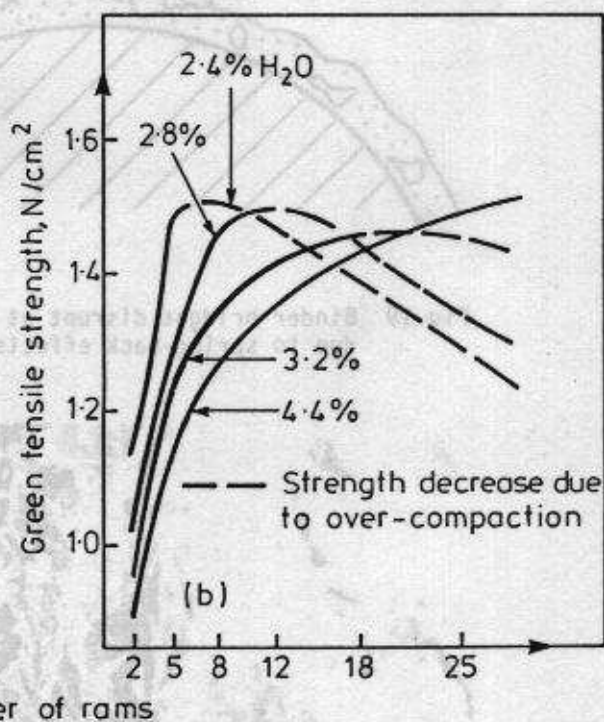
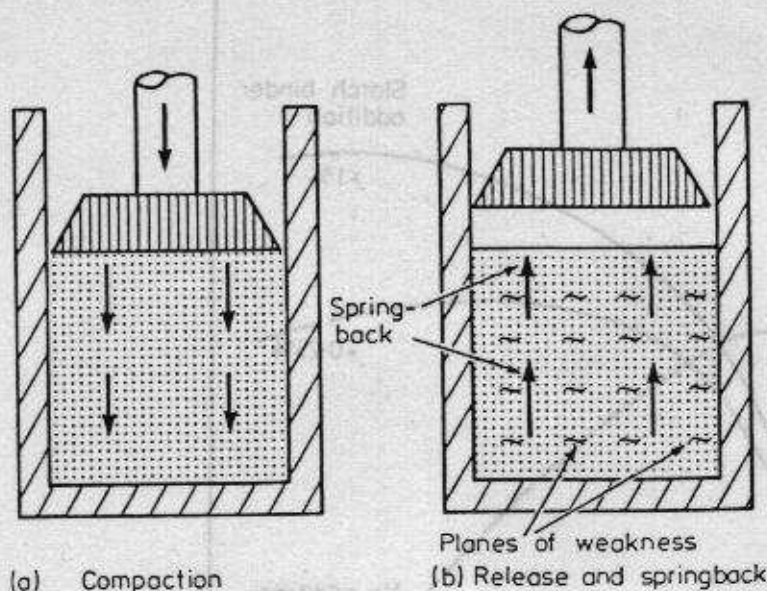


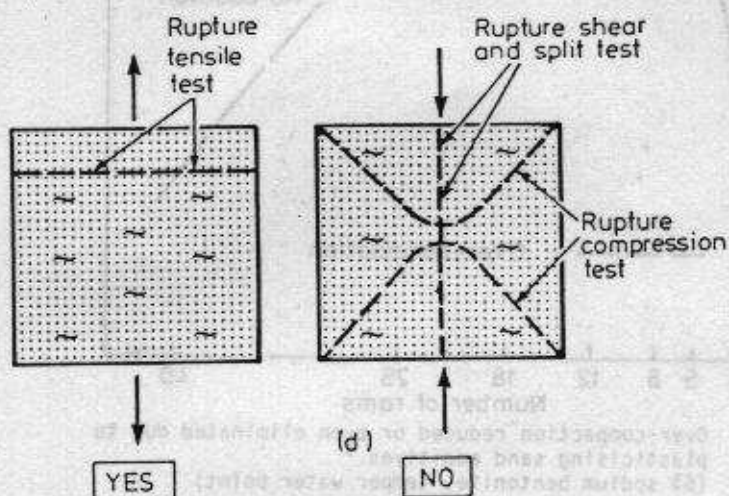
Fig. 22b

Fig. 22 'Over-compaction' results in spring-back and tensile strength decrease (22b). Compression strength is not affected (22a).¹ (5% bentonite)



(a) Compaction

(b) Release and springback



(c) Sand testing influenced by spring-back

Fig.23 Tensile strength measurements are influenced by planes of weakness due to spring-back effects (23c). Conventional test procedures operate along divergent plans of rupture (23d) (Schematically)

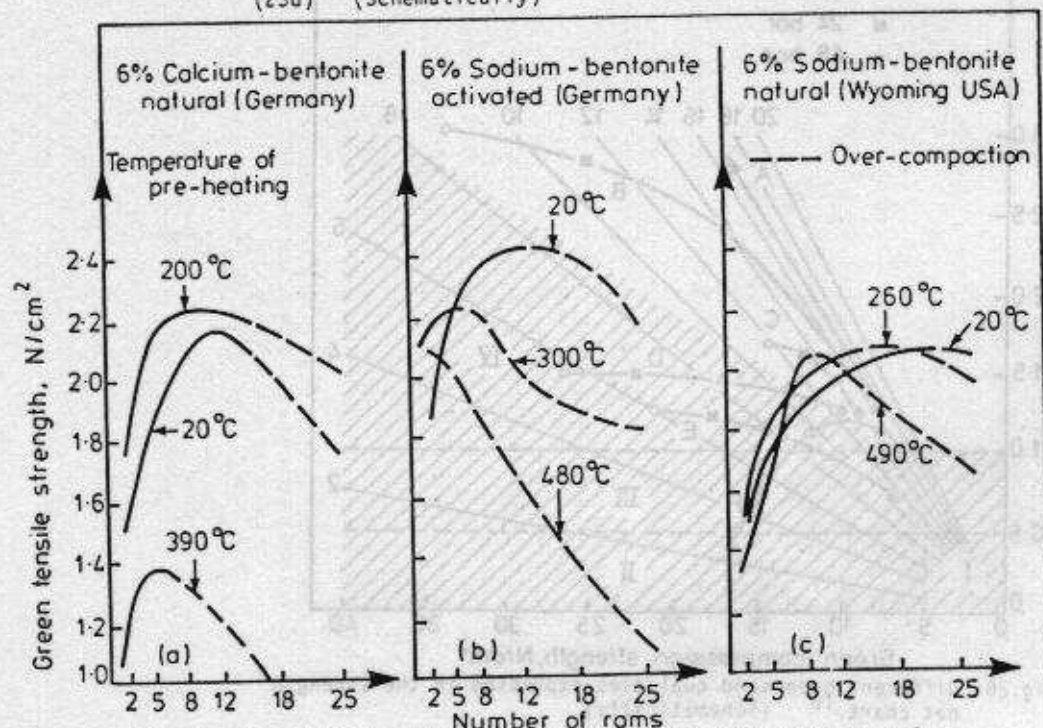


Fig.24 Strength behaviour varies with thermal decomposition of different types of bentonites.¹

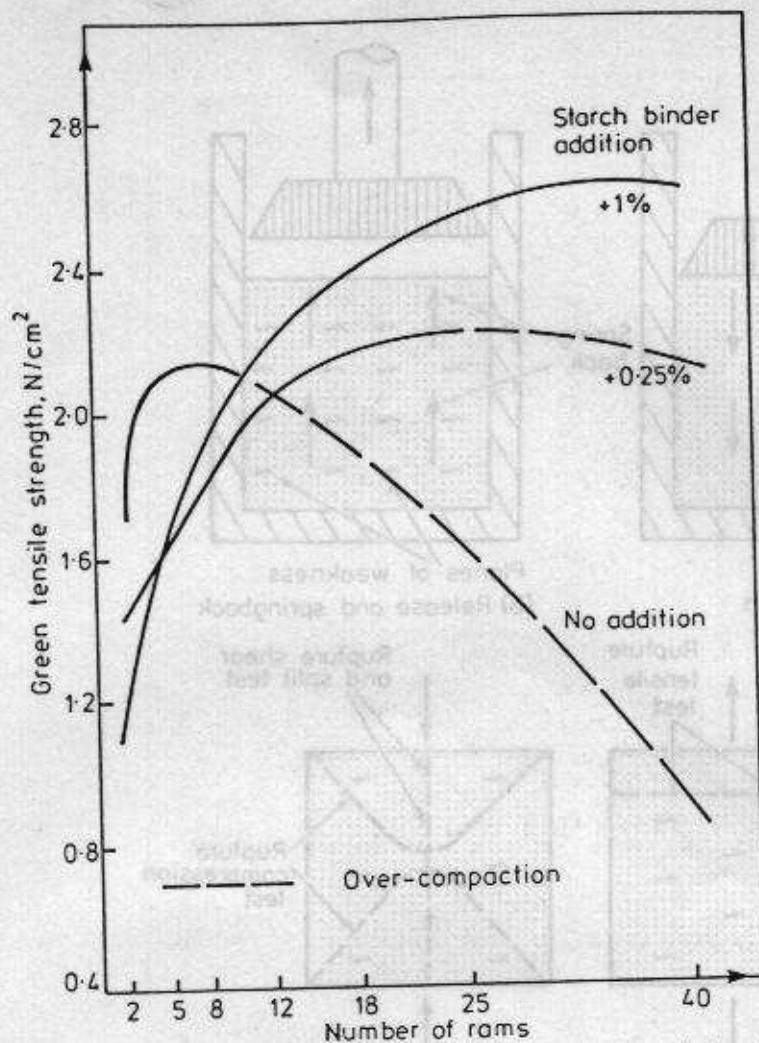


Fig. 25 Over-compaction reduced or even eliminated due to plasticising sand additives. (6% sodium bentonite, temper water point)

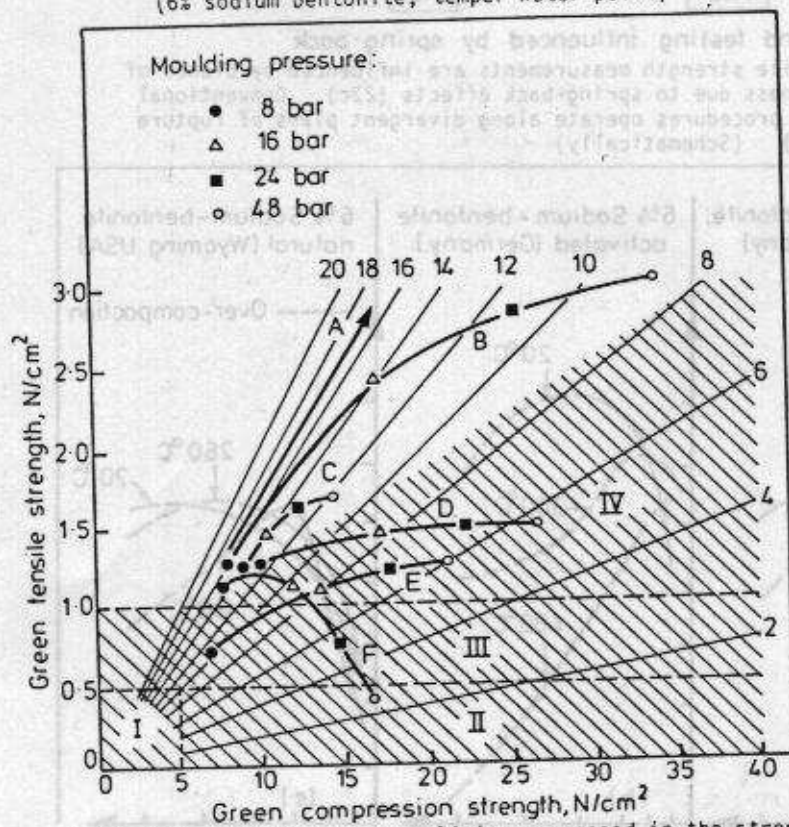


Fig. 26 Different greensand qualities expressed in the strength net chart. ¹⁰ (Schematically)

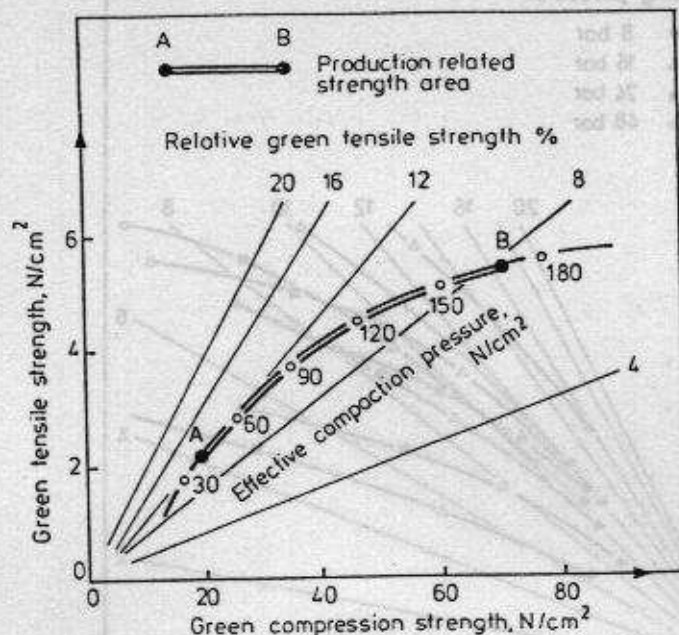


Fig. 27 Production-related strength net chart established by means of pressure gauges (see Fig. 9). (Greensand and production conditions of a German grey iron foundry. Production range between A&B.

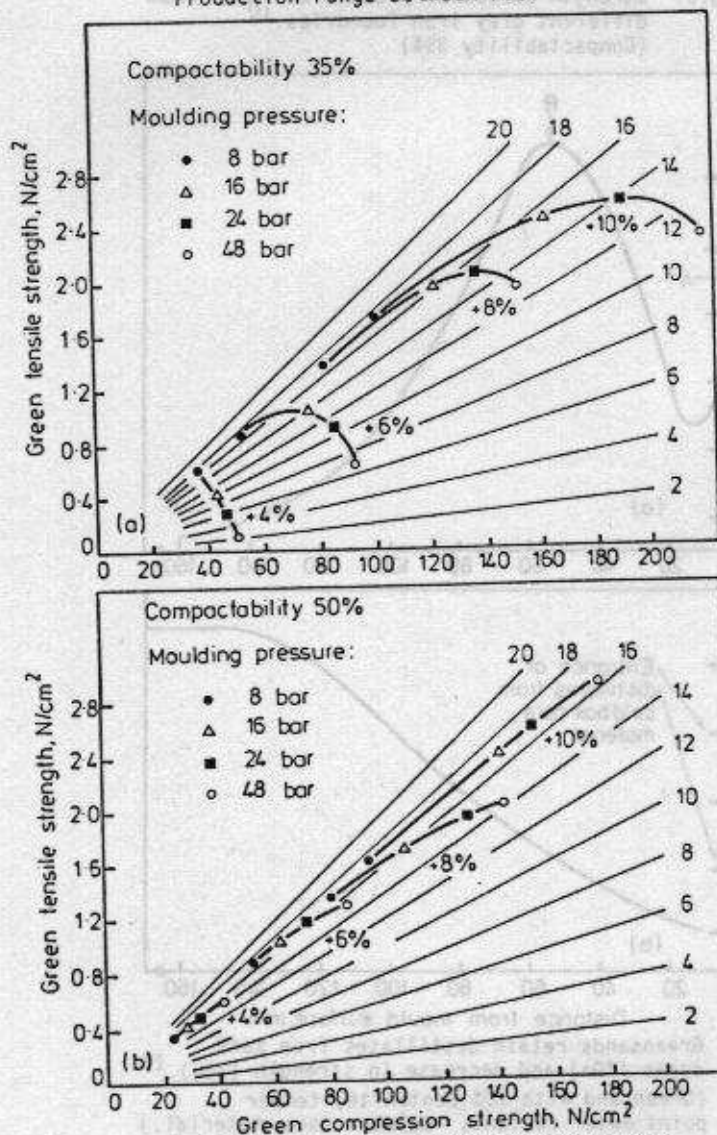


Fig. 28 Influence of bentonite content at two different moisture levels in net chart representation.¹⁰ (Bentonite from Wyoming, USA)

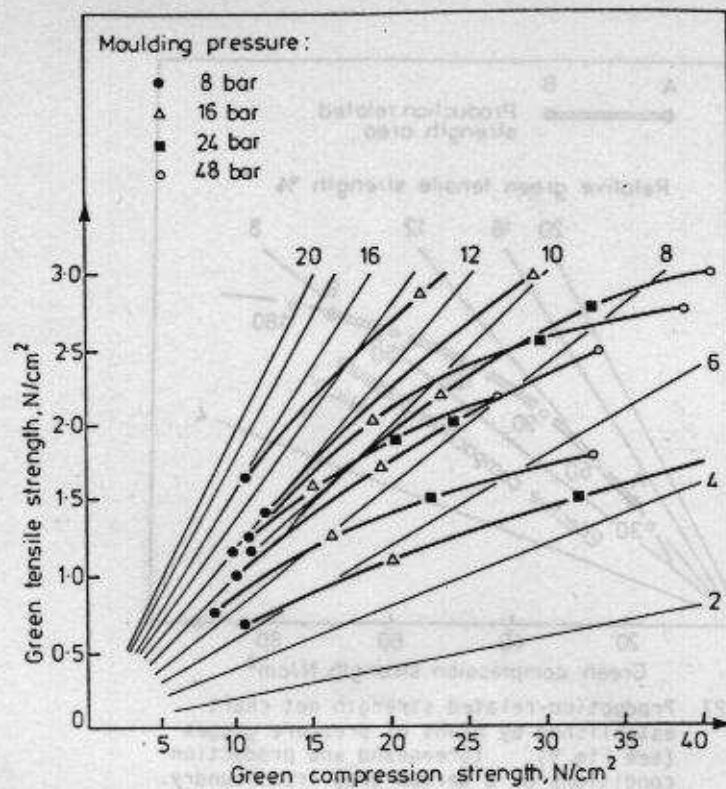


Fig.29 Strength curves of production sands from different grey iron foundries.¹⁰
(Compactability 35%)

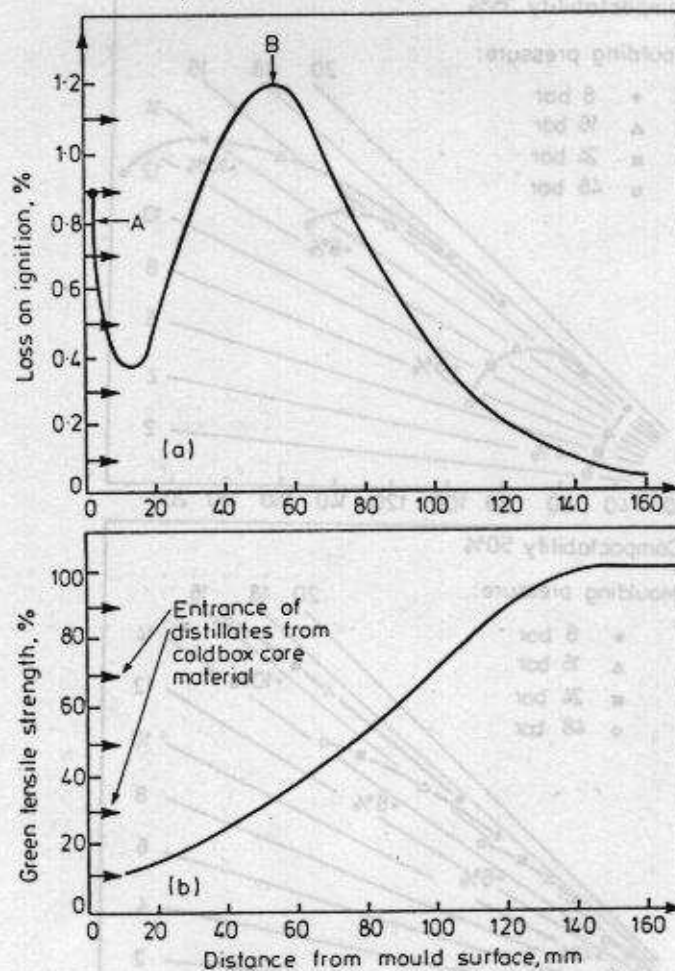


Fig.30 Greensands retain distillates from sand cores (30a) and decrease in strength (30b).¹²
(Greensand with 10% bentonite, temper point water content; coldbox core material.)

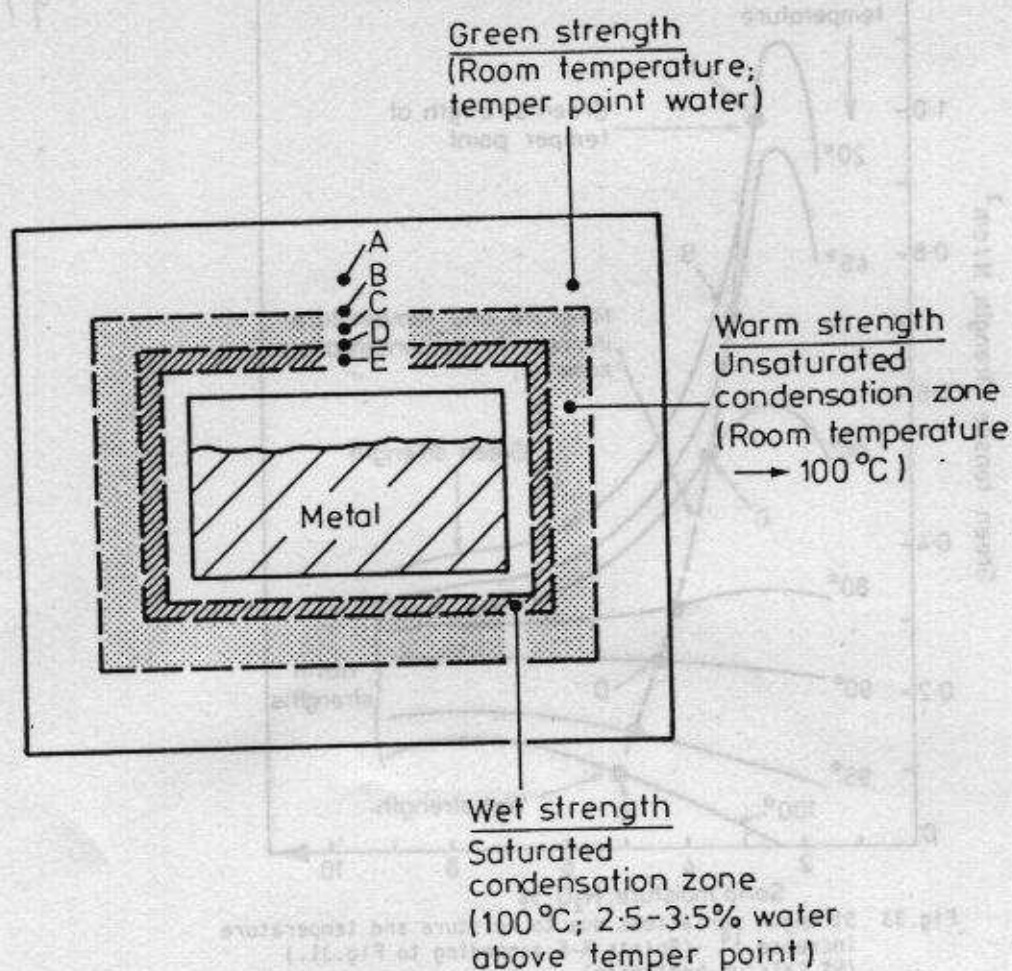


Fig.31 Zones of different strengths in a greensand mould during filling with liquid metal. (Schematically)

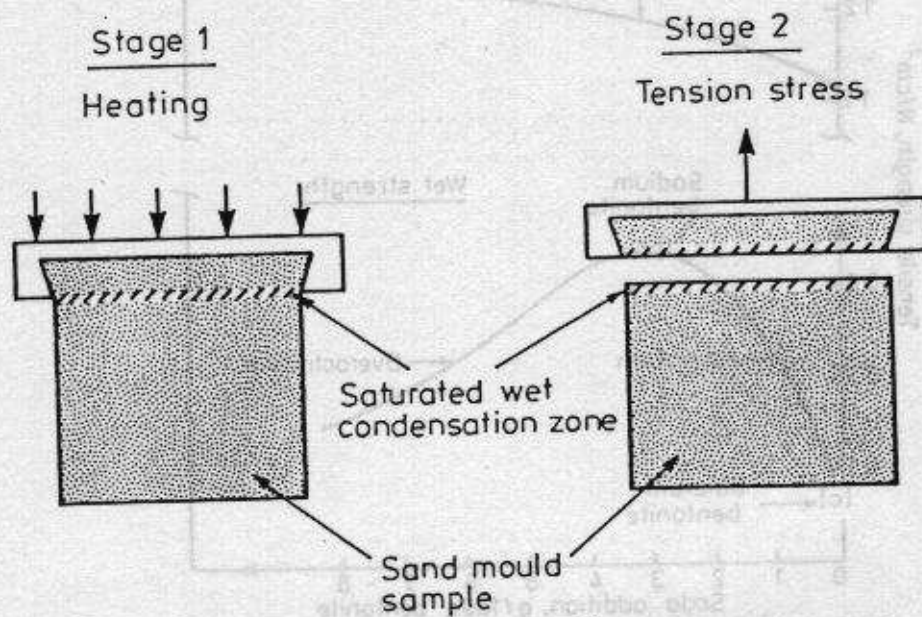


Fig.32 Principle of wet strength testing.¹³ (Type PNZ testing equipment of Georg Fischer AG, Schaffhausen, or H.W. Dietert Co., Holly, USA.)

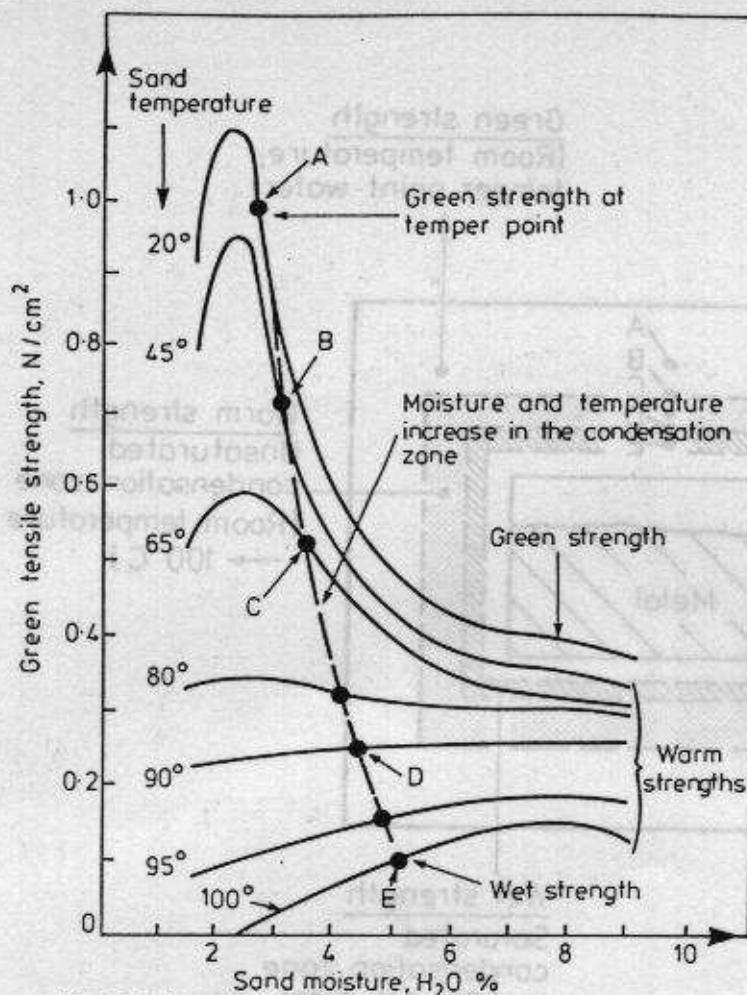


Fig.33 Strength variations due to moisture and temperature increase. (Points A-E according to Fig.31.) (5% Calcium-bentonite)

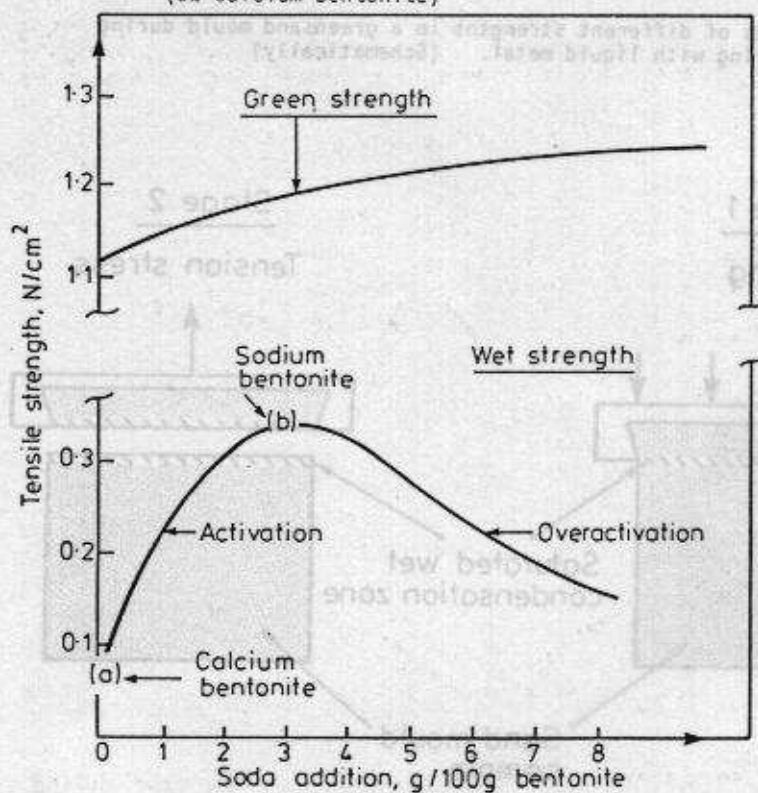


Fig.34 Activation result indicated by wet strength changes (lower part with 'activation curve,' but no influence on green strength (upper curve)^{13,15} (6% calcium bentonite, compactability 40%)

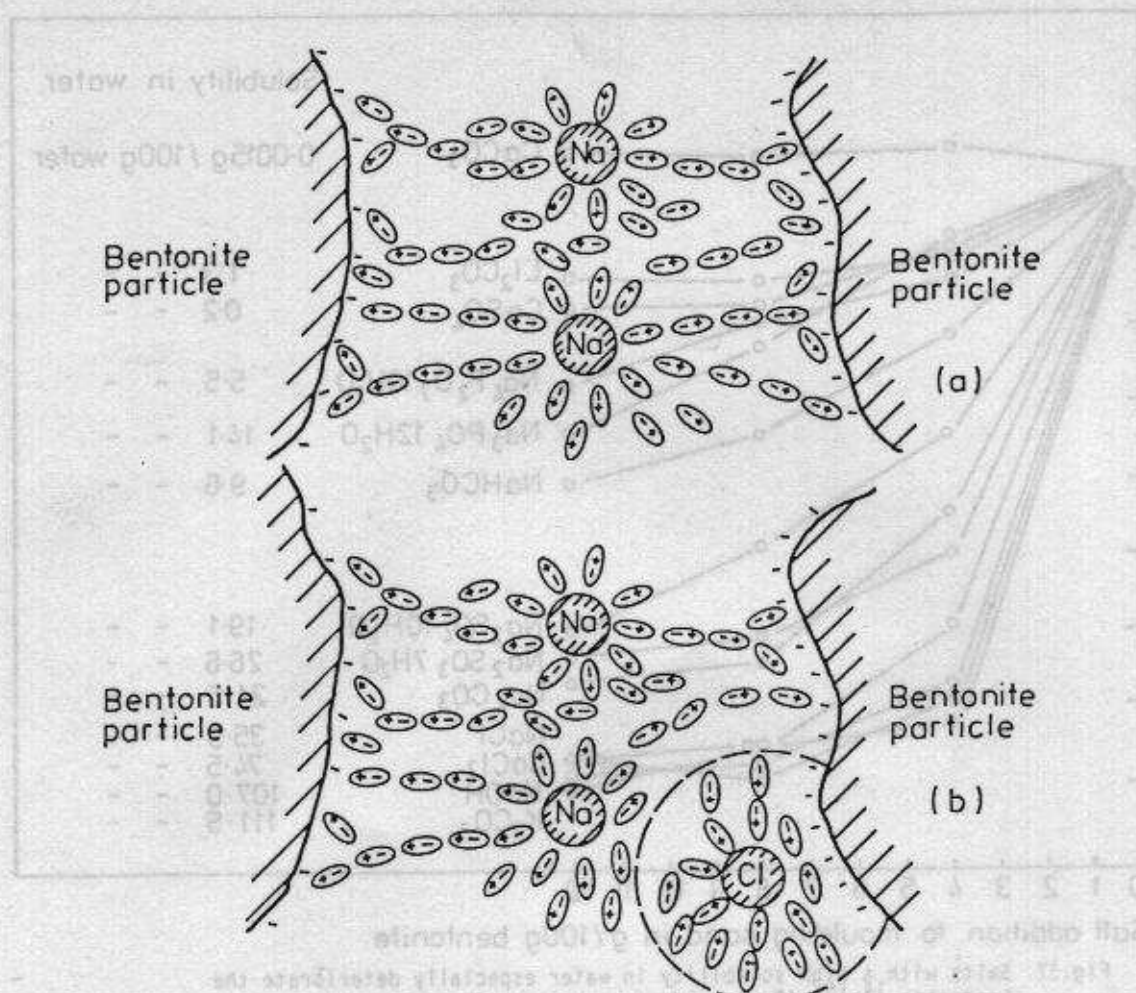


Fig.35 Adsorbed cations account for the strength of the water bridges and thus the wet strength (above). Free 'roving' ions interfere in the bridge bonding and reduce the wet strength (below).

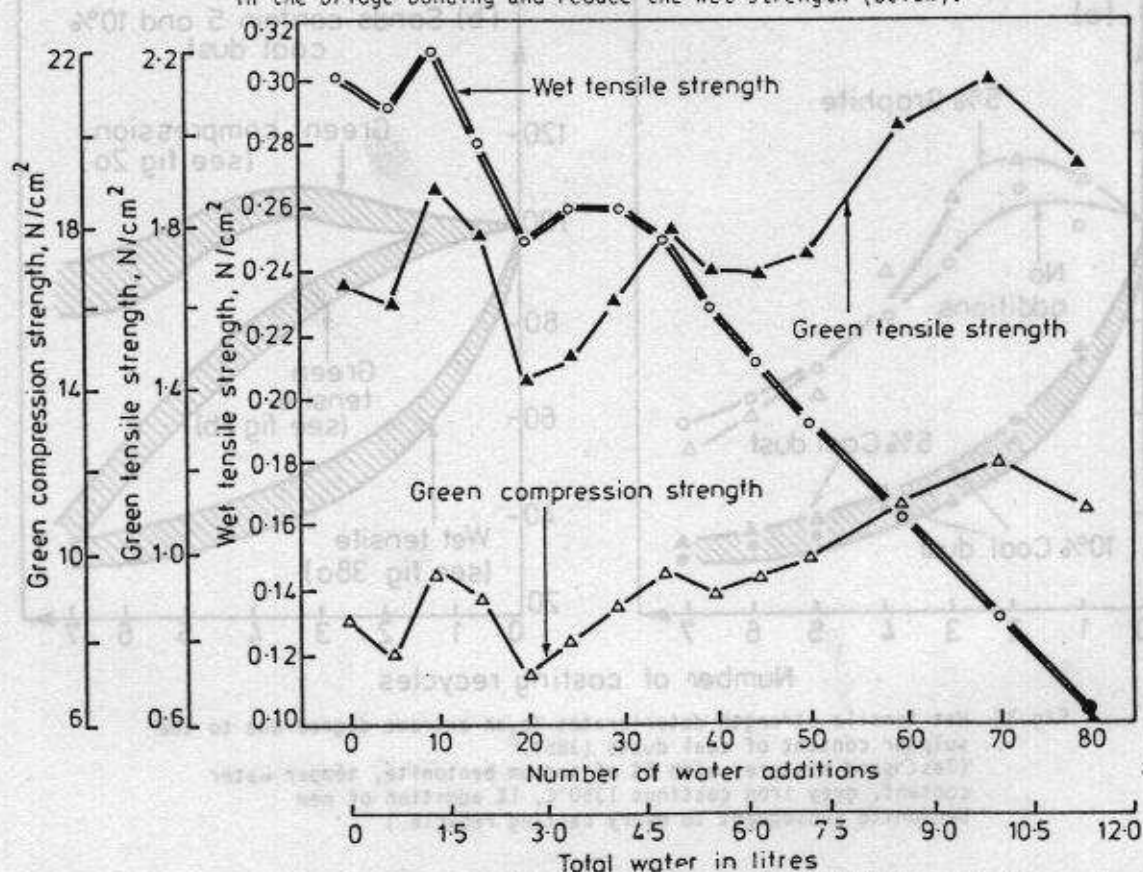


Fig.36 Repeated greensand recycling causes electrolyte accumulation and wet strength deterioration without influence on green properties. 14,15 (Test sand mixture with 6% of sodium bentonite, temper water content.)

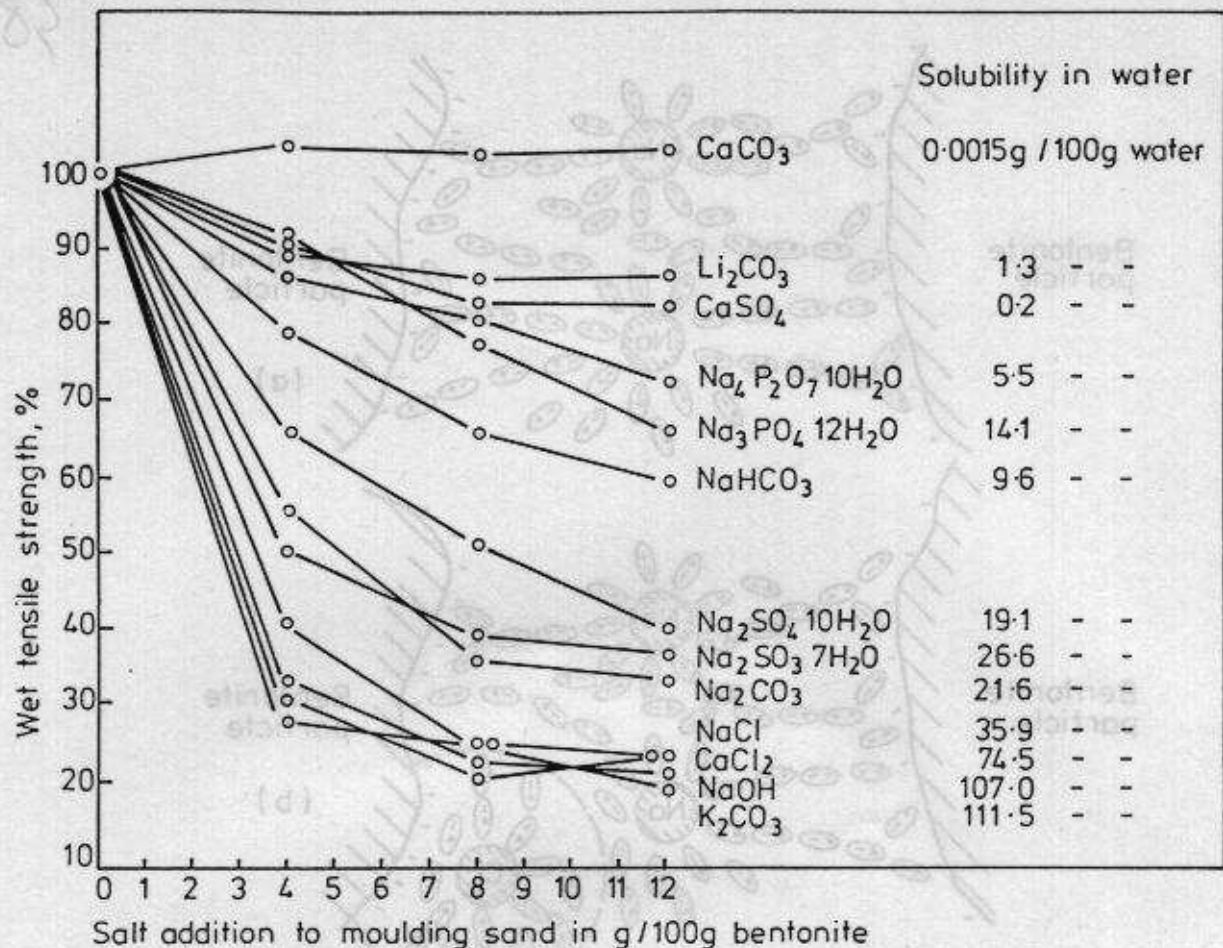


Fig.37 Salts with a high solubility in water especially deteriorate the bentonite.^{14,15} (Test sand mixtures with 6% of sodium bentonite, temper water content.)

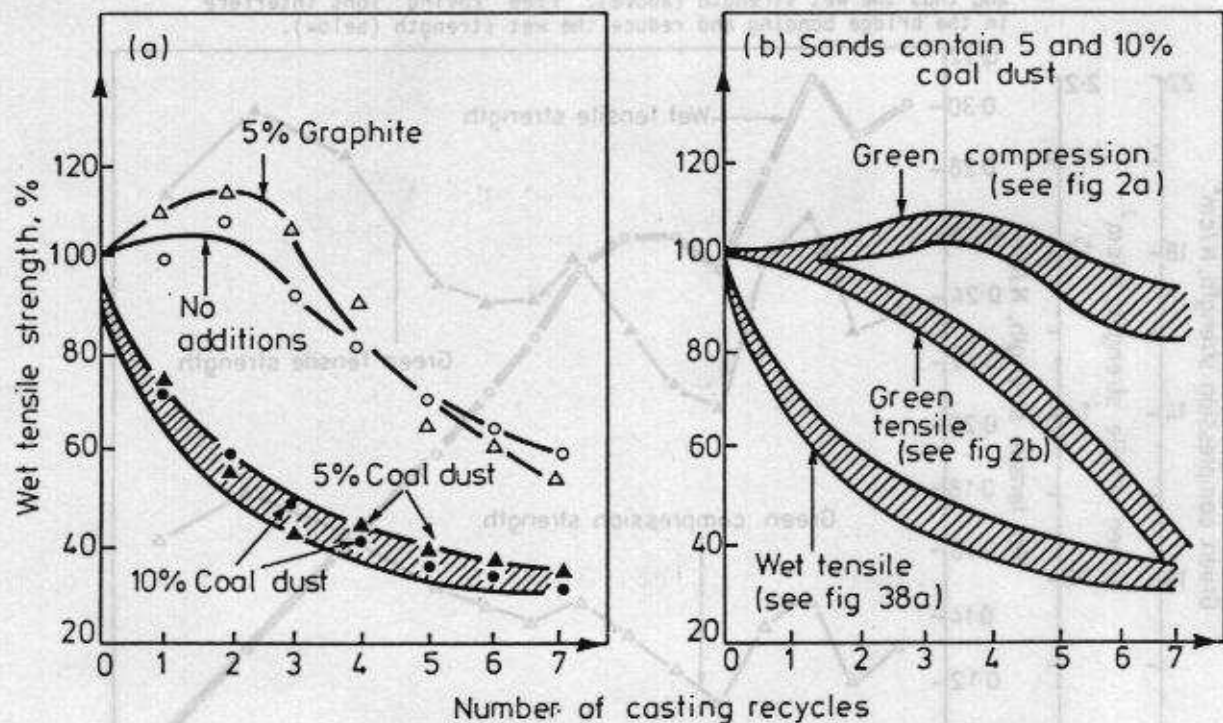


Fig.38 Wet tensile strength deteriorates to an extreme degree due to the sulphur content of coal dusts (38b).² (Test sand mixtures with 6% of sodium bentonite, temper water content, grey iron castings 1350°C, 1% addition of new bentonite subsequent to every casting recycle.)

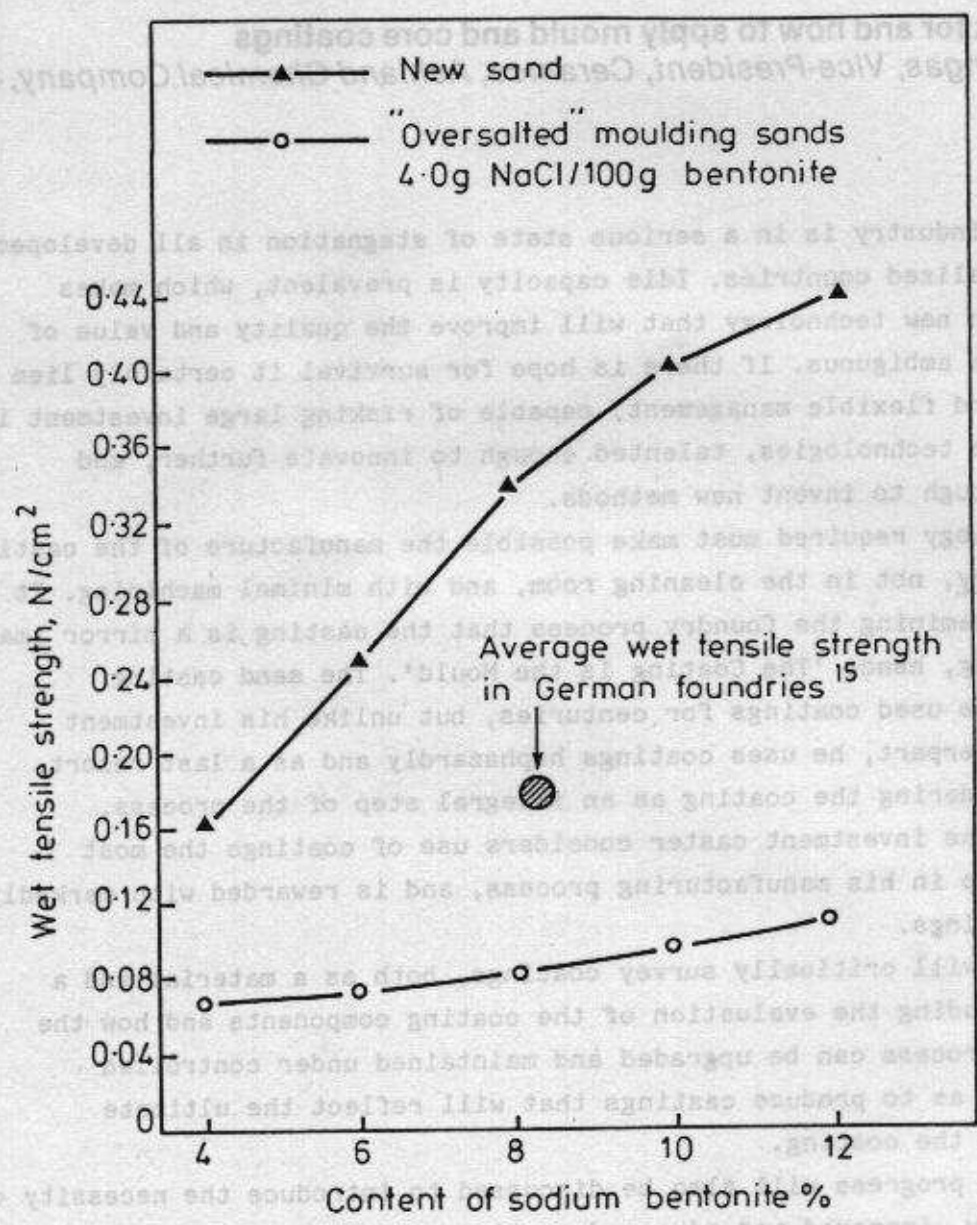


Fig.39 Impairment of production sands as indicated by strongly reduced wet tensile strength values.¹⁵
(Sodium bentonites, temper water content.)

Introduction

The past decade has seen the flight of metal casting production to the far corners of the world. To counter this trend the industrialized