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Steel Pipe for Slurry Pipelines

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Canalisations en acier pour les pipe-lines destinés aux boues
Tubería de acero para líneas de tubería de líquidos pastosos
スラリパイプライン用スチールパイプ
泥浆管道用的钢管
انابيب الفولاذ الخاصة بخطوط انابيب الملاط . بقلم انش . جابسلر .

Summary

In every instance, steel pipe fulfills the requirements demanded of slurry pipelines. They have the strength to absorb stresses, the essential deformability for their manufacture, pipe-laying, and operation, and the toughness required from the point of view of fracture mechanics. They allow the construction of technically reliable, economical pipe connections and are distinguished in particular by their weldability, oriented towards modern pipe-laying methods. Wear due to erosion and corrosion presents no problem when provision has been made for wear from the very beginning in the design, construction, and operation of slurry pipelines.

The high level of pipeline technology in gas and oil pipelines characterised by steel piping and distinguished by technical safety, economy, non-pollution, and reliability, can be transferred to slurry pipelines without any restriction.

1. Introduction

In general, the term "slurry pipeline" is understood to mean pipeline transportation systems in which significant quantities of solids can be conveyed as a pumpable mixture often over long distances on a fluid mechanics basis using carrying fluids — mainly water to date [1,2]. Because of the internal pressure stresses prevailing, slurry pipelines in operation are made almost exclusively of steel pipe and, like gas and oil pipelines, the sections of pipe are normally butt-to-butt welded to form an endless pipe and are laid in the earth [3]. Pipelines form the principal components of such transportation systems and account for much more than half the overall capital investment costs for example on long-distance pipelines.

The properties of the pipes, the materials of which they are made, and the dimensions upon which the optimum transportation conditions depend, are, therefore, of decisive importance for the technical safety and economy of this transportation system which is uncomplicated in principle and is environmentally acceptable.

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2. Influencing Factors, Loads, and Demands on the Pipes

The influencing factors which affect the condition of the pipes are numerous. In particular, as shown in Fig. 1, they are a product of the properties of the solids and the carrying fluid and of the operating and pipe-laying conditions. These influencing factors are of decisive importance for the loads to which the pipes are subjected, e.g., internal pressure, which is a product of pressure loss and pressure surges, and can be static or dynamic or for possible wear on the inside surface of the pipe.

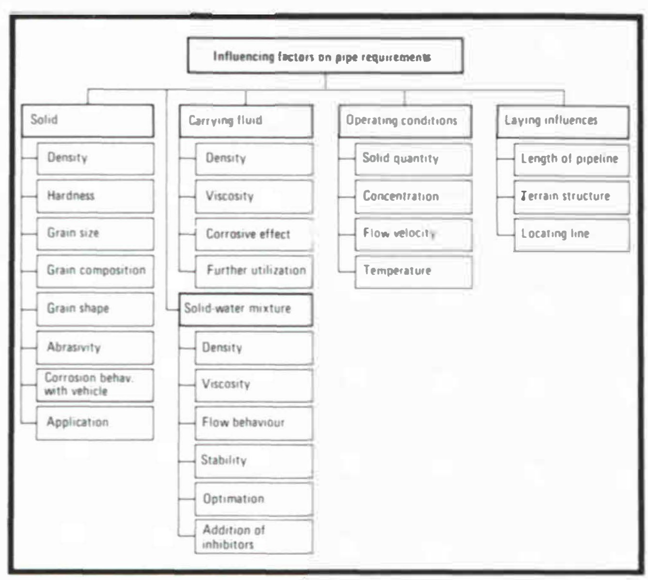

Fig. 1: Influencing factors on pipe requirements

The technical demands on the properties of the material and the design of the pipes is determined by these loads which require differing assessments in respect of their effects upon the service life of the pipes, Fig. 2.

Of decisive importance are the strength properties to absorb the effects of internal pressure and additional loads as well as the deformability required for manufacture, laying and operation, as well as the toughness properties of significance for fracture mechanics behaviour even at sub-zero temperatures. Also of importance are the types of technically safe pipe connections, and, particularly for long-distance pipelines, the weldability oriented towards modern

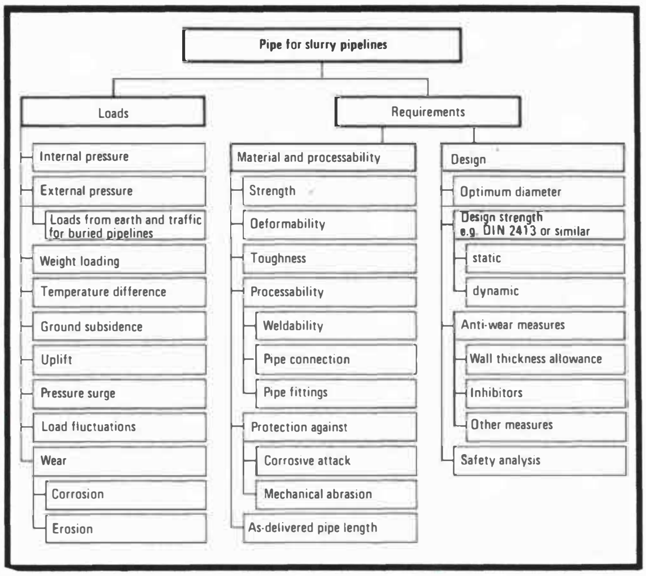

Fig. 2: Loads and requirements on pipe for slurry pipelines

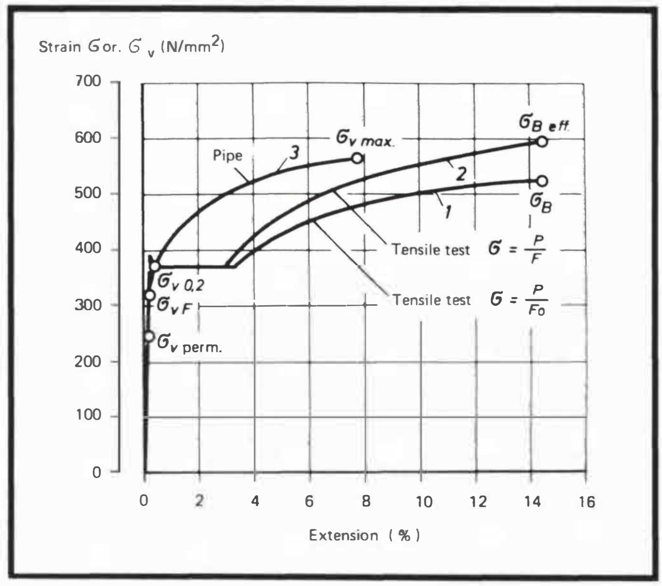

Fig. 3: Stress-deformation curve for pipes and tensile tests — Example X52

pipeline laying methods with equivalent properties in the weld metal and parent metal. One special requirement — and this is where slurry pipelines differ from pipelines for pure flowing media — extends to the resistance to erosion and non-susceptibility to corrosion of the materials or to measures which can favourably affect the wear behavior of the materials for a given service life.

3. Properties of Steel Pipe for Slurry Pipelines

3.1 Pipe Materials

Steel pipe can be optimally matched to the service requirements, a considerable contribution being made by the characteristic stress-deformation behaviour of the pipeline steels. This behaviour is characterized by high yield stress, up to which purely elastic extension is present. Depending upon the type of steel, mimimum yield strengths of 210 N/mm² to more than 500 N/mm² are attained at a modulus of elasticity of 2.10^5 N/mm². The latter value, 500 N/mm², applies, for example, to high-tensile pipe steels such as are required nowadays for transportation systems for compressed gases and products.

However, the loadability of the steels is by no means exhausted when the yield point is reached. The flow curve includes the plastic range in which the load capacity can be increased to the maximum load point by utilizing a large deformation reserve due to the strain hardening capacity of the steel. Fig. 3 shows, for example, the behaviour of material X52, and that for the uniaxial tensile test with assumed marked flowing range in comparison with that of a pipe under internal pressure with a steady flowing curve.

As a rule, the behaviour of the steel in the plastic range is not taken into consideration when calculating the wall thickness of the pipe. Here, the yield point or the proof strength with 0.2 % permanent or 0.5 % overall deformation is used whereby the acceptable level of operating loads must retain a sufficiently large margin of safety. The coefficients of safety are stipulated in DIN 2413, which is the calculation standard for steel pipe prevailing for the Federal Republic of Germany, at 1.4 to 1.6 for pipes laid in the ground. These coefficients of safety are a function of the deformability of the steels expressed by the elongation at fracture determined in a uniaxial tensile test. The strength calculation which is operative for non-strain-hardening material behaviour, thus features a reserve against the fracture failure limit which, nevertheless, is partially utilized to compensate for peak stresses and local plastical deformations.

For steel slurry pipelines, preferably standard pipe steels are used. Special-alloy steels or QT steels are limited to short pipeline lengths or experimental lines. Taking pattern from the developements for gas and oil pipelines, the German technical conditions of delivery to DIN 17172 "Steel pipes for pipelines" are used for orientation and also DIN 1626 and DIN 1629 for welded or seamless pipe of unalloyed steels for lower demands (Table 1). In this connection, the API standards 5L "Line Pipe", 5LS "Spiral-Weld-Line Pipe" and 5LX "High-Test Line Pipe", issued by the American Petroleum Institute (API), are worthy of particular mention (Table 2). This was the first technical specification for delivery of any kind in the pipeline construction sector. The national standard specifications are substantially oriented towards the API standards so that the steel grades given in DIN 17172 are also comparable with those in the API standards [4, 5].

Table 1 provides an overview of the technical properties of the principal steel groups. They are according to the calculation of wall thickness arranged by minimum yield strengths which also stipulate the designations in accordance with DIN 17172. The designations of DIN 1626, DIN 1629, and API standards contain the tensile strength as a feature.

Further development of the yield strength from 210 N/mm² to 480 N/mm² was a result of the necessity to match pipe materials to the ever-increasing stresses incurred in the course of time with increasing length and increasing diameter without allowing the wall thickness to increase into uneconomical manufacturing ranges.

The tensile strength rises with increasing strength group somewhat slower than the yield strength whereby the ratio yield point to ultimate strength rises. The permitted upper limit is $\sigma_S/\sigma_B = 0.9$.

Strength group DIN	As-delivered condition to DIN	Yield strength (N/mm²)	Tensile strength (N/mm²)	Extension %
St 34-2 StE 210.7	1626 Sheets 3 + 4 17172	206 210	333 to 412 320 to 440	26 26
St 37-2	1626 Sheets 3 + 4 1629 Sheet 3 17172	235 235 240	360 to 440 340 to 440 370 to 490	23 25 24
St 42-2 St 45 StE 290.7	1626 Sheets 3 + 4 1629 Sheet 3 17172	255 255 290	410 to 490 440 to 540 420 to 540	20 21 23
StE 320.7	17172	320	460 to 580	21
St 52.3 St 52 StE 360.7 StE 360.7 TM	1626 Sheets 3 + 4 1629 Sheet 3 17172 17172	355 355 360 360	510 to 610 510 to 610 510 to 630 510 to 630	22 22 20 20
StE 385.7 StE 385.7 TM	17172 17172	385 385	530 to 680 530 to 680	19 19
StE 415.7 StE 415.7 TM	17172 17172	415 415	550 to 700 550 to 700	18 18
StE 445.7 TM	17172	445	560 to 710	18
StE 480.7 TM	17172	480	600 to 750	18

Impact work as mean value of three samples for pipe smaller than 500 mm dia. 47 joule
In general, 27 joule obtains as mean value for pipe greater than 500 mm dia., but 31 joule for parent metals of strength groups from StE 385.7

Table 1: Pipe steels for slurry transport (DIN)

Strength API	As-deliverd condition	Minimum yield strength (N/mm²)	Minimum tensile strength (N/mm²)	Minimum elongation e on 2" (50.8 mm)
Grade A	API 5L/5LS	207	331	
Grade B	API 5L/5LS	241	413	
X 42	API 5LS/5LX	289	413 *)	
X 46	API 5LS/5LX	317	434 *)	$e = 625\,000 \frac{A^{0.2}}{U^{0.9}}$
X 52	API 5LS/5LX	358	455 *)	
X 56	API 5LS/5LX	386	489 *)	A= Cross section of tensile specimen (inch²)
X 60	API 5LS/5LX	413	517 *)	
X 65	API 5LS/5LX	448	531 *)	U= Tensile strength (psi)
X 70	API 5LS/5LX	482	565	
X 80	API 5 LU	550	655 to 861	
X 100	API 5 LU	690	758 to 931	

*) At any wall thickness for pipe under 508 mm dia. and wall thicknesses greater than 9.52 mm, for pipe over 508 mm dia.

Table 2: Pipe steels for slurry transportation (API)

Elongation at fracture decreases with increasing strength group, whereby to DIN 17172 18 % is specified as the minimum extension.

Parallel to the increase in strength, there was the development of field weldability and — with regard to adequate resistance to crack initiation and crack propagation — also the improvement in toughness properties, expressed as a measurable parameter in the notch impact toughness. This resulted in a top limit for the carbon content. As a criterium was introduced the carbon equivalent, a figure influencing the hardness of the heat affected zone and, consequently, characterizing the weldability, which represents the ratio of carbon to the other alloy constituents.

The yield strength for steels up to material group X 52, which was the highest available quality grade until the beginning of the 1960s, is obtained by raising the carbon and manganese contents. Up to X 60, additional increase in strength can be brought about by additional microalloying with carbide- and nitride-forming elements such as, say, vanadium and niobium through precipitation hardening and grain refinement. Here, the carbon content is normally up to 0.2 %.

No further increase in strength properties can be obtained on normalized steels because otherwise the simultaneous demand for good field weldability and improved toughness can no longer be fulfilled. Consequently, a new rolling process, known as thermo-mechanical treatment, was introduced for welded pipe whereby a special hot forming technology was applied during the rolling of the sheet or strip. By this means, yield strength increases can be obtained up to quality grade X70 with a minimum yield strength of 480 N/mm² with simultaneous reduction in carbon content and carbon equivalent. Pipe of thermo-mechanically treated initial materials exhibit a highly favourable welding behaviour and good toughness properties. For this reason, this process is also used for lower strength grades, e.g. X 60.

To increase the strength values above X 70 or above X 60 for seamless pipe, quenching and liquid tempering is used [6, 7].

Steel pipe of all strength classes can be considered for slurry pipelines (Fig. 4). For long-distance pipelines where internal pressures up to 100 bar can be expected, high-tensile qualities are particularly suitable, for example X 60 or even higher than X 60 for larger diameters. They require lower wall thicknesses to absorb stresses of the internal pressure, which can be of benefit when considering the wear allowances. In addition, the higher-tensile strength groups have a more favourable erosion behaviour which can even be further improved in special circumstances by taking specific measures.

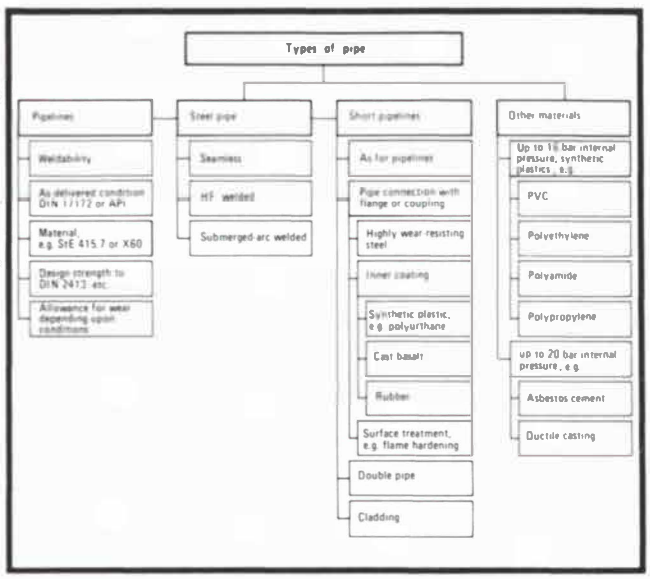

Fig. 4: Pipe material for slurry pipelines

Non-weided — mostly short — pipelines which are laid with flanges or couplings can also be provided with a special type of anti-wear protection such as, for example, by lining with rubber or synthetic plastics on a polyurethane or polyamide basis. The plastic material can be applied either by spraying, sintering, or can be shrink-fitted in the form of plastic sheeting. Lining with cast basalt has also proven its worth both with highly erosive material and also with corrosive carrying media. To increase the resistance to erosion, measures can also be taken to increase the hardness of the material on the inside surface of the pipe. Such treatment as flame-hardening is known whereby the surface is heated locally to hardening temperature such that the core properties are retained. By contrast, the inner layer of double-wall pipe is made of a quenched and tempered steel with high carbon content, hardened to approx. 650 HB, whereas the outer pipe consists of a normal pipeline steel which has to absorb the stresses.

Mechanical abrasion can be limited by all of these measures and also by the use of particularly wear-resistant steels which cannot be welded by normal methods, e.g., manganese steels (40 Mn 4, 46 Mn 5). But corrosion cannot always be limited.

Finally, the type of pipe and the pipe material depend upon economical considerations whereby the question of pipe connections in conjunction with the stress and the as-delivered length has also to be taken into account.

3.2 Pipe Dimensions

The diameter of slurry pipelines depends upon the amount of solid material at optimum velocity and optimum concentration. Diameters are between 100 mm and approx. 500 mm for known pipelines in operation. Fig. 5 shows, for example, a pipe diameter of 457 mm for the Black Mesa coal pipeline for $5 \cdot 10^6$ t coal per year and 508 mm for the Samarco ore pipeline for $12 \cdot 10^6$ t ore per year. Serious planning, primarily in the United States of America, on the other hand, envisages amounts of solids up to $35 \cdot 10^6$ metric tons of coal per year which would require pipe diameters up to approx. 1000 mm for single-strand lines [8].

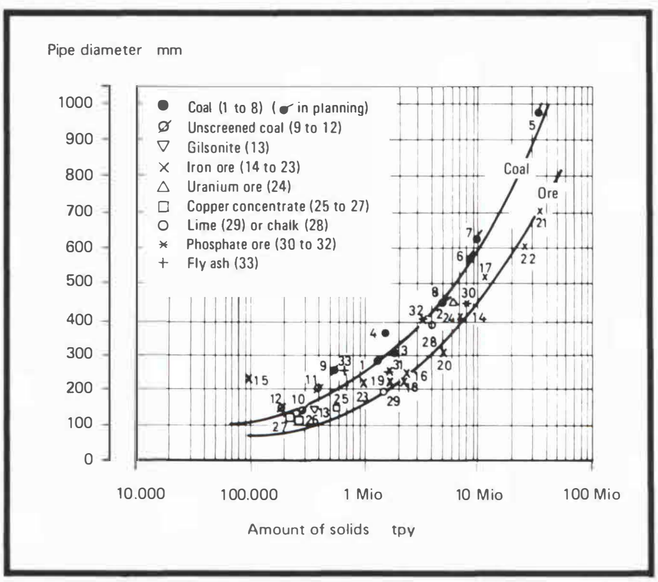

Fig. 5: Relationship between pipe diameter and amount of solids to be conveyed

Steel pipe can be supplied in lengths up to 18 m for all these diameters with the requisite wall thicknesses for internal pressure and wear allowance. Depending upon diameter, a difference should be made in the main between three methods of manufacture.

a) Seamless pipe, manufactured by hot rolling from a cast billet or ingot up to 660 mm O.D.
b) HF-resistance welded pipe, manufactured from continuously cold-formed steel strip by longitudinal pressure welding (with 1.0 welding factor) up to 508 mm O.D.
c) Submerged-arc welded large-diameter pipe in the dimension range greater than 500 mm, manufactured from formed sheet or strip with a longitudinal seam or a helical seam in the case of spiral welded pipe.

All three pipe manufacturing processes, for which quality control inspections are being conducted from steel manufacture to finished product, are permissible and can be regarded as being of equivalent value. Each process has its own significance with regard to production reliability, depending upon diameter, wall thickness, material and costs.

4. Effects of Wear

In comparison with the optimum properties of steel pipe for slurry pipelines described, the amount of wear to be expected presents a less favourable picture. Wear can cause a time-related reduction in the wall thickness of the pipe, limiting the service life, and consequently has to be taken into account at the design stage. Wear is the product of a number of individual influencing factors, an overview of which is provided in Fig. 6.

Wear includes mechanical abrasion (erosion) by the solids conveyed as well as corrosion by the carrying medium, i.e., water. The interaction of these two factors can provoke very high rates of wear because the solids flowing through the pipe and grinding at the pipe wall constantly produce new areas for corrosive attack.

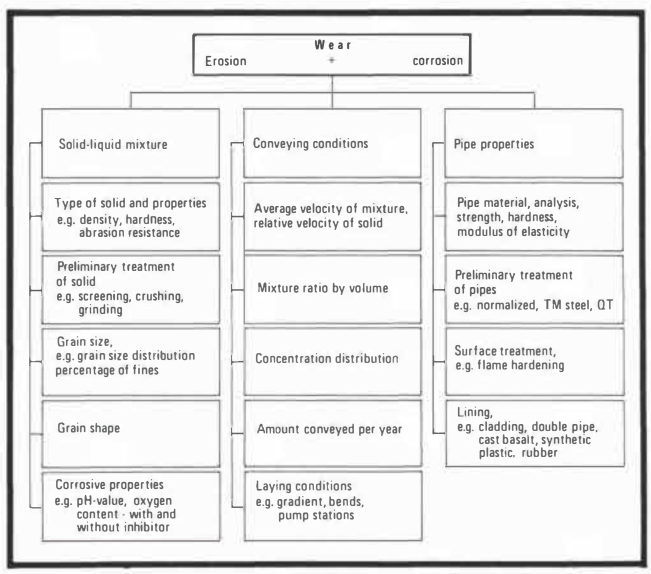

Fig. 6: Influencing factors on pipe wear

4.1 Corrosion

Depending upon the flow velocity and turbulence, corrosion is influenced by the dissolved oxygen, the pH-value of the solid and water slurry, acids, and salts. Free oxygen maintains the reaction of corrosion [9] and has to be kept away from the pipe wall or has to be reduced. Since pipe linings are only practicable in pipelines at low pressures in nonwelded short lines and, in addition, due to the fact the practical efficiency of mechanically degassing the solid and water slurry still has its short-comings, protective measures have been taken to date only by reducing the dissolved oxygen by the addition of inhibitors [10].

The pH-value is also controlled by additives to ensure that it does not fall below a specific level, e.g., a value of 9, because the rate of corrosion would then rise considerably as can be seen in Fig. 7 from the results obtained by Gandhi [11].

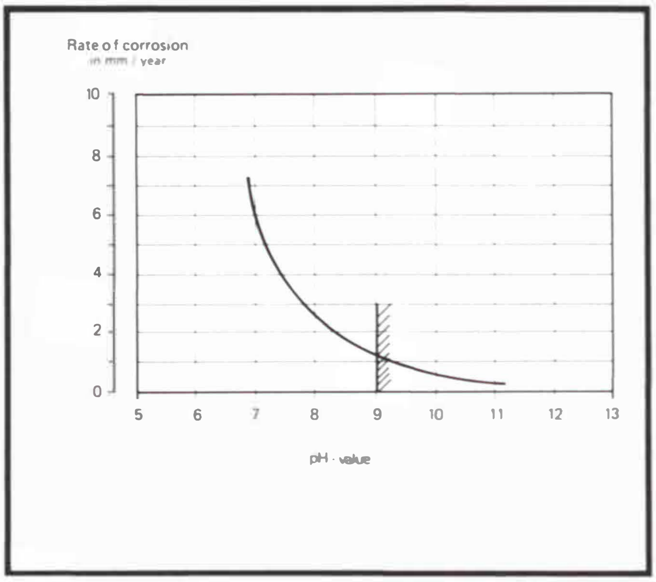

Fig. 7: Influence of pH-value on the rate of corrosion in accordance with [11]

4.2 Erosion

The properties of the solid, the pipe material, and the conveying conditions are the prime factors for mechanical abrasion. The conveying velocity, which affects the magnitude of the wear rate to the second or third power [12, 3], is an influencing factor of decisive significance. For coal and products with similar Miller indices, the connection between erosion and velocity, described as loss of wall thickness, has been found to be $\Delta s = 0.97 \cdot Fr^3$ per 10^6 t amount of solid conveyed, whereby $Fr = v/\sqrt{D \cdot g}$ represents the Froude Number related to the pipe diameter [13].

Fig. 8 shows this relationship which contains a generalization in so far as it relates to grain sizes from 1 to 60 mm. Nevertheless, the result contains not only pure abrasion but also an indeterminate amount of corrosion.

The influence of the pipe material on abrasion is characterised in principle by a decreasing rate of wear with increasing hardness of the pipe material [14]. Fig. 9 also shows this behaviour as an example for several steels from St 37 up to X 70 which had been subjected in part to differing heat treatment. Admittedly, the values indicated contain a percentage of corrosion due to the test circumstances. With inhibited corrosion preventing the influence of dissolved oxygen (Fig. 8, lowest value of St 37 material), the amount of wear can be one decade lower as can be confirmed in the literature [10].

4.3 Practical Measures

Designing steel pipe for slurry pipelines to optimum transportation conditions for the overall system leads to grain sizes of the solid, conveying velocities, and concentrations which contain pure erosion within limits for virtually all solids. Nevertheless, the grinding effect of the solids will destroy passivating protective linings so that corrosion can become fully effective. The magnitude of the rates of wear to be expected can then amount to up to 4 mm/year depending

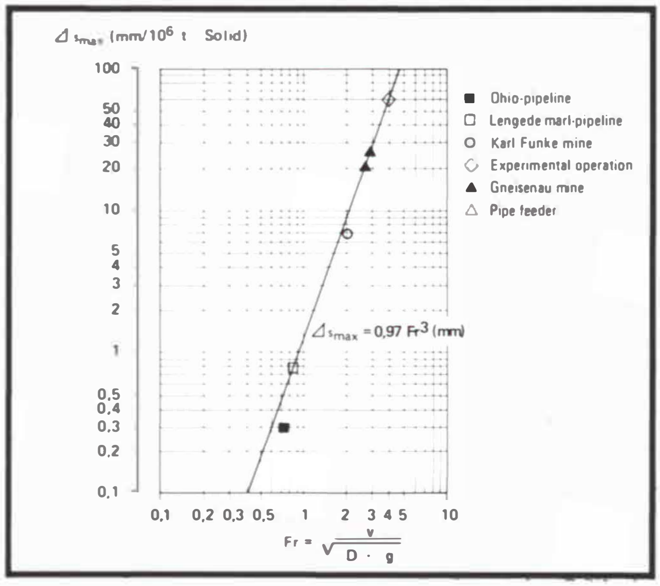

Fig. 8: Wear losses in conveying solid-water slurries in different pipelines

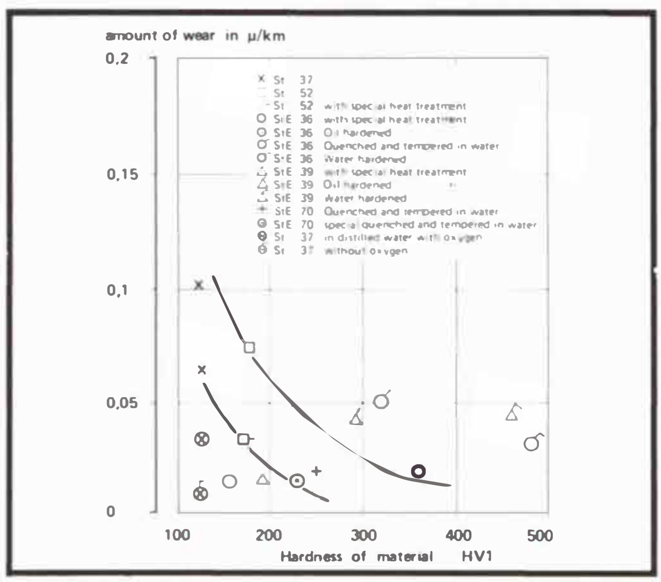

Fig. 9: Grinding wear on steels in an ore-water slurry (5:1 ore to water mixture) determined by the pot wear process

upon the solid material properties [15] which would render this method of transportation of no interest under normal circumstances. An adequate solution would then have to be found on a case-by-case basis. The following possibilities exist:

1. In advance, there would be an allowance in wall thickness to cover the rate of wear.

2. Corrosion would be inhibited by means of inhibitors with simultaneous adjustment to the pH-value and by taking the residual wear into account by wall thickness allowance.
3. The pipes could be treated or internally lined.
4. The carrying medium should be of a non-corrosive type, e.g., methanol.

Thick-walled pipe and also lined piping severely raises the capital investment costs whereas the addition of inhibitors increases the operating costs. Fig. 10 shows the ratios using, as an example, 5 million t per year coal being conveyed through a pipeline, 457 mm in diameter, over a distance of 440 km. Assuming an annual rate of wear of 1.3 mm/year without the use of inhibitors, a wall thickness allowance of 32.5 mm would be required for a service life of 25 years, incurring an annual outlay of 19 million DM for the assumed rates of costs and capital service.

The wear on steel pipe caused by erosion and corrosion, therefore, does not represent a technical or economic problem if it has been given due consideration from the very beginning during the design, construction, and operation of slurry pipelines.

5. Conclusion

To recapitulate, it may be regarded as established fact that the high level of pipeline technology for gas and oil pipelines, which is characterised by the optimum properties of the steel pipe and is expressed in terms of technical safety, economy, reliability and — last but not least — by its environmental acceptability can also be transferred to slurry pipelines without any limitation.

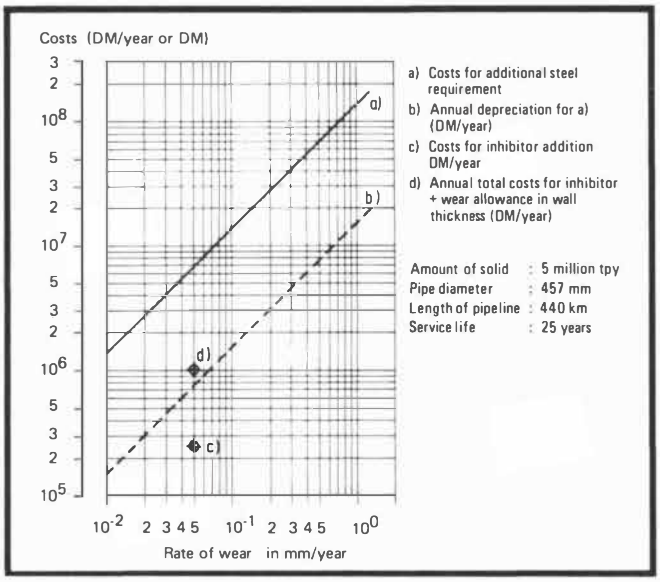

Fig. 10: Expenditure to take account of wear

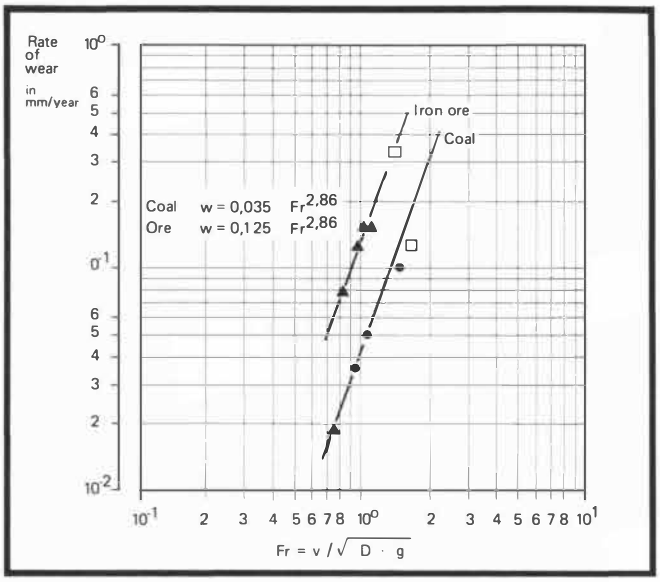

Fig. 11: Basis for annual rates of wear in relation to the Froude Number

When sodium sulphite is added as an inhibitor sufficient to maintain a rate of wear of 0.05 mm/year, operating costs of DM 0.03/t solid or DM 150,000 DM/year will be incurred at a 50 % concentration by weight. Taking into account plant and test costs to the amount of 100,000 DM/year, the final figure required for inhibiting would amount to DM 250,000/year, i.e., DM $1.1 \cdot 10^{-4}$/(t·km). Assuming the overall transportation costs for slurry handling to be DM 0.02/(t·km) [16, 10], the costs for inhibiting would amount to 0.5 %. If the wall thickness allowance is taken into account at 0.05 mm/year, the costs of wear would amount to $1 \cdot 10^6$ DM/year or DM $4.6 \cdot 10^{-4}$/(t·km), accounting for 2 % of the overall transportation costs.

The results show how negligibly small the additonal costs are to ensure technically reliable transportation.

Consequently, wall thickness allowance with simultaneous inhibiting will be combined in practice on non-protected slurry pipelines. Experiments and the experience gained on existing pipelines will give wall thickness allowances which would appear advisable. Fig. 11 gives a basis for such calculations for coal and ore lines which presupposes that the lines are designed for optimal transportation conditions.

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