mately eight different authors in this paper's reference list who have used this same or a very similar correlation in their study of asphalt cement. Furthermore, it has a very practical value in refinery planning as well as in meeting current specifications.

REFERENCES

1. Fisher/Tag Manual for Inspectors of Petroleum. Fisher Scientific, Chicago, Ill., 1954.
2. W.W. Kraft. Vacuum Distillation of Petroleum Residues. Industrial and Engineering Chemistry, Vol. 4, 1948, p. 807.
3. Foster-Wheeler Engineering Corporation. Solvent Deasphalting, Hydrocarbon Processing, Houston, Tex., Sept. 1982, p. 190.
4. J.A. Gearhart and S.R. Nelson. ROSE Process for Solvent Extraction. Proc., Fifth Industrial Engineering Conservation Conference, Houston, Tex., April 1983.
5. J.A. Gearhart and L. Garwin. ROSE Process Improves Resid Feed. Hydrocarbon Processing, Houston, Tex., May 1976.
6. S.P.A. Snamprogetti. Asphalt Blowing. Hydrocarbon Processing, Houston, Tex., Sept. 1982, p. 209.
7. L.W. Corbett. Reaction Variables in Air Blowing of Asphalt. Industrial Engineers Chemical Process Research & Development, Vol. 14, 1975, p. 181.
8. L.W. Corbett and U. Petrossi. Differences in Distillation and Solvent Asphalt. Industrial Engineers Chemical Production, Research & Development, Vol. 17, 1978, p. 342.
9. Test Method for Separation of Asphalt into Four Fractions. ASTM D 4124-82. Annual Book of ASTM Standards, Philadelphia, Pa., 1983.
10. L.W. Corbett and H.E. Schweyer. Viscosity Characterization of Asphalt Cement. ASTM Special Technical Publication 532. ASTM, Philadelphia, Pa., 1973.
11. Viscosity Graded Asphalt Cement. AASHTO, Washington, D.C., 1978.
12. Specifications for Viscosity-Graded Asphalt Cement for Use in Pavement Construction. ASTM D 3381. ASTM, Philadelphia, Pa., 1981.
13. J.Ph. Pfeiffer and P.M. Van Doormaal. Rheological Properties of Asphaltic Bitumen. Journal of the Institute of Petroleum, Vol. 22, 1936.
14. J.A. Lefebvre. A Modified Penetration Index for Canadian Asphalts. Proc., Association of Asphalt Paving Technologists, Vol. 39, 1970.
15. V.P. Puzinauskas. Properties of Asphalt Cements. Proc., Association of Asphalt Paving Technologists, Vol. 48, 1979, p. 646.
16. Grading of Paving Asphalts by Viscosity at 140°F Versus Penetration at 70°F. ASTM Special Technical Publication 424. ASTM, Philadelphia, Pa., 1966.
17. Symposium on Viscosity Grading of Asphalts. Highway Research Record 350, HRB, National Research Council, Washington, D.C., 1971, 63 pp.

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Refinery Economics

K. W. HOLBROOK

ABSTRACT

The following aspects of refinery economics are covered: relation to asphalt-cement production; the outlook for crude-oil supply and demand; refinery data and the statistics of refining operations; past, current, and future changes in the economics; the effect of those changes on asphalt-cement supply, price, and availability; and a review of the general outlook for asphalt production.

Refinery economics is a subject about which there are many questions. Some assumptions can be made as to what we think is going to happen in the refining industry, but the economics changes rapidly. The subject of this paper is not just refinery economics but also how refinery economics relates to asphalt-cement production. The paper will cover the outlook for crude-oil supply and demand; refinery data and the statistics of refining operations; past, current, and future changes in the economics; the effect of those changes on asphalt-cement supply, price, and availability; and a review of the general outlook for asphalt production.

It can be seen from the data in Table 1 on world oil consumption that the 1960s was the decade of

TABLE 1 World Oil Consumption

Time Period	Percentage of Growth	Characteristics
1960s	6/year	Expanding world economies
1970s	3/year	Slowing growth and energy conservation
1980-1985	0/year	Flat world economies and greater energy conservation
1985-1990	1-2/year	Improved economic conditions

resids, use fluxants, or even air-blow if necessary, all of which may be predetermined through a laboratory effort.

Viscosity Graded Specifications are More Rational

Based on temperature susceptibility alone, the AASHTO Table 2 specification is more critical than those specifications used in European and Eastern countries. Figure 12 shows a comparison between the viscosity graded system and a typical European specification for two penetration grades. Whereas the viscosity grades are controlled by the viscosity-penetration relationship, the European specifications rely on a softening point-penetration relationship or penetration index (13). By translating other data, it is possible to plot the two systems together, which shows that the viscosity-penetration line must be at a higher level in the Figure 12 plot when meeting an AC-20 specification (Table 2) compared with a 60/70 penetration grade under the European specifications.

To further illustrate the differences between the two systems, Table 3 was prepared to present the range in test values, first, when meeting the minimum specification requirements, and second, when all crude sources were involved. If the reasoning can be accepted (16,17) that viscosity at 140°F is a more appropriate control of asphalt-aggregate mix qualities than penetration hardness, then it can be rationalized that grading by viscosity offers a better opportunity for controlling mix qualities than when using the penetration system as permitted under crude source limitations.

TABLE 3 Differences Between Grading Systems

AREA	GRADE	VISCOSITY DEPENDS ON CRUDE SOURCE MIN	VISCOSITY DEPENDS ON CRUDE SOURCE ALL	PENETRATION DEPENDS ON CRUDE SOURCE MIN	PENETRATION DEPENDS ON CRUDE SOURCE ALL
USA	AC-10(2)	800-1200	800-1200	80-105	80-200
USA	AC-20(2)	1600-2400	1600-2400	60-77	60-130
EUR	80/100	790-1100	790-4200	80-100	80-100
EUR	60/70	1300-1600	1600-6700	60-70	60-70

Additionally, the viscosity graded system includes controls on hardening through the use of thin film oven tests, with its limitation on viscosity increase and minimum ductility. The European system is still based on the loss-on-heating test and a decrease in penetration, which is appreciably less limiting.

SUMMARY

1. Crude petroleum varies in its make-up distillable fractions as well as in its bitumen content. These differences are considerable and are an important consideration in the manufacture of asphalt cement.

2. Straight reduction by distillation is a necessary first step in the processing of all crudes. Solvent deasphalting and supercritical extraction are other processes that yield fractions that are sometimes used in asphalt cement. Continuous air-blowing is applied only when low viscosity resids need to be adjusted or upgraded.

3. The largest volume of asphalt cement manufactured in the United States is manufactured by straight reduction to grade from either a single crude or from a mixture of crudes. Blending of fractions is done under the limitation of meeting specification requirements.

4. Crudes may be arbitrarily classified according to API gravity, which is relatable to distillation cut-points as well as to the composition of the asphalt derived therefrom and their physical properties.

5. The viscosity-penetration relationship, identified with temperature susceptibility, is a very useful characteristic when selecting crude feeds for asphalt cement specification compliance.

6. Viscosity graded (Table 2) specifications as used in the United States are more rational than the penetration-softening point controlled system practiced in European and Eastern countries.

Discussion

Richard L. Davis*

The author is to be complimented on a very fine and informative presentation. During his presentation, he mentioned that viscosity determinations at 140°F showed considerable variation when run on asphalts that had nearly the same penetration at 77°F. This statement points out a major problem in the asphalt industry.

The dangers of extrapolation are well-known. In the case of viscosity measurements of asphalt, there are a number of sources of variation. The viscosity of different asphalts are affected to a greater or lesser extent by both temperature and stress. In addition to the variations due to temperature and stress, the random error variations of the test methods used to measure viscosity, such as the capillary tube and penetration device, are rather large. When the test results of these methods are extrapolated to other temperatures and stresses, the precision limits are greatly expanded. This means that we should extrapolate as little as possible and that we should not be surprised when test results at different temperatures show considerable variation.

Author's Closure

Thank you for your comments in which you pointed out the dangers of extrapolating viscosity and penetration values to other temperatures and under different conditions of stress. You suggested that the relationship as used may not be as real as apparent because some of the true causative factors are not being subject to measurement.

Whereas you choose to use the term "extrapolation," that is, going beyond the limiting degree of measurement, the writer believes that the term "correlation" or "correspondence" between test values is more appropriate to the case in point. Seldom can we control all of the independent variables, either in testing or, more important, in the composition or crude source involved. That, however, does not mean that we should not investigate some of the more apparent causes and effects, which would lead to a better understanding of the complexities of this subject. As evidence of this, you will find approxi-

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greatest growth. The growth in consumption was about 6 percent per year because the economies were expanding both in the United States and overseas. Economies looked good, cars were getting bigger, people were driving further, and there were no carpools or vanpools; consequently, demand grew rapidly. In the 1970s, helped by the Arab oil embargo, that growth slowed to about 3 percent per year. Energy conservation became a fact of life; carpooling became more common and even though the economies were stable, there was significant reduction in the demand for crude oil and petroleum products. In the first half of the 1980s there was basically no growth at all, or possibly even a decline: It has been a no-growth period because of the significant energy conservation that everyone is practicing.

Poor economies overseas and only a moderately improving economy in the United States have kept refinery economics in the doldrums. For the last half of the 1980s some improvement has been projected--possibly 1 to 2 percent growth in petroleum products and crude oil. Of course, this projection is based on some significant assumptions: The world economies are going to improve, there will be relative stability within the Organization of Petroleum Exporting Countries (OPEC) on crude-oil production and pricing, and the political climates in the world will remain stable. The primary concern, of course, is the Middle East.

REFINERY OPERATIONS AND UTILIZATION

Refinery operations slowed dramatically in the early 1980s because of the poor world economy. Refinery operations have also been affected by government regulations. Before the 1980s, the U.S. government assisted small refineries and the refinery industry, support that has now been eliminated in many cases. This has had a detrimental effect on the refining industry, particularly small operations. Further, energy conservation has resulted in significant reduction in petroleum product demand.

Refinery utilization was at a low of 62 percent in 1982, whereas in the late 1970s refineries operated in the range of 80 to 90 percent utilization. Because of this low utilization more refineries have shut down. As a result, 35 percent of the 324 refineries have been shut down in the last 4 years, and more shutdowns can be expected in the next year or so. Many of those refineries were the smaller ones. In excess of 20 percent of the U.S. refining capacity has been affected by the economy and the economics of refining.

DOMESTIC ASPHALT-CEMENT PRODUCTION

About 36 percent of all U.S. refineries produce asphalt cement. However, not all crudes yield heavy bottoms that make asphalt and as a result only about 4.2 percent of the crude that is processed results in asphalt cement. The United States has a refining capacity of 18 million barrels per day of crude; 4.2 percent of that is 756,000 barrels per day of asphalt cement, which is equal to 50 million tons of product a year. Demand in the United States is in the range of 25 to 30 million tons annually, so in 1982 there was a more than adequate supply of asphalt-cement capacity to meet the needs of the industry. With the refinery shutdowns mentioned earlier, that capacity of 50 million tons or 756,000 barrels per day has been reduced significantly. Nevertheless, there is still adequate refinery capacity to meet the annual demand.

Asphalt cement is a major product of small refineries but only a small part of the production of many large refineries. Refineries with less than 10,000 barrels per day of crude capacity yield 7 percent asphalt production. On the other hand, the larger refineries, in general, yield only 2 percent asphalt production. The smaller refineries were the ones hit hardest by the fluctuations in the economy and by the change in government legislation. Their closings significantly affected the asphalt-cement supply.

OUTLOOK

Refineries, as a result of the change in economics, have begun modifying their processes to meet changing market conditions and also to meet changing crude availability. The increasing price of crude and petroleum products has made residual heating oil uneconomical as compared with coal and natural gas. A recent statistic illustrates that 1 million Btu's of heat generated by a petroleum product cost about $5. A comparable amount of Btu's generated by coal is about one-third of that, or $1.50. The incentive to convert from petroleum products to nonpetroleum energy sources is clear. Of course, that conversion does not automatically result in a $3.50 savings because the user will incur some conversion cost in changing a facility from a petroleum to a nonpetroleum energy user. Nonetheless, there is significant incentive to convert and that has caused changes in petroleum product demand.

Crude quality is also changing. A variety of different gravities of crude are available in the world. Right now the crude processed in the United States is about 60 percent light with 40 percent of the heavier type. The known reserves in the world are the heavier crudes such as those from Venezuela, Mexico, and a number of other countries. The crude that is being discovered is also of the heavier nature. As a result, it is predicted that by 1990 there will be a significant switch from lighter to heavier crudes. That means more bottoms available to convert to asphalt cement.

Pricing of the crudes certainly has an effect on availability and what the refinery is going to process. In the past, the light crudes have sold at a premium. With the decline in price of the light products recently and the improvement in the price of the bottom of the barrel, demand for heavier crude has increased. This phenomenon is expected to continue for a short period of time. So it may be seen that there are many factors that go into the overall analysis of refinery economics.

RESIDUAL UPGRADING PROJECTS

Because of changing economics, refineries are modifying their methods of operation by upgrading the bottom of the barrel with conversion projects. In the past 3 or 4 years more than 30 major conversion projects have been started, which will be completed soon. These new projects will be capable of converting in excess of 500,000 barrels per day of bottoms to light products, reducing the asphalt supply. However, soon after these projects were in operation, the economics changed, making these residual-conversion projects much less attractive than they had appeared to be a year earlier.

Economics dictates the operations of a refinery. In the following discussion crude costs are related to refined products and asphalt-concrete prices, and two cases in which a refiner has to decide whether to produce another barrel of asphalt or to convert that asphalt to light products are reviewed. Two types of refining methods are compared:

- A refinery producing asphalt and
- A refinery capable of converting all the asphalt into light products using a coker (no asphalt is produced).

Case 1

Historically the price of asphalt concrete has been an economic loss to the refinery and was propped up by the higher value of the lighter products. By a simple arithmetic calculation one can determine whether asphalt will recover raw material costs. As an example, sour crude is delivered to the refinery at about $33.50 per barrel; the average selling price for asphalt cement is $143 per ton, which, when converted to barrels, is $25.58 per barrel. In this case the refinery is losing $7.92 per barrel on the asphalt cement. In other words, the refiner must recover that $7.92 in the high value of other products or that refinery is not going to be in existence for long. In this case the refinery is not even making raw material costs, much less operating costs or profit, on that particular segment of the refinery operation.

To illustrate this point a little better, a typical refinery (Table 2) that yields 43,479 barrels per day with an investment of $52 million will be used. These products are yielded: motor gasoline,

TABLE 2 Case 1: Typical Refinery Economics

Item	Unit Amount and Price	Amount ($)
Products		
Motor gasoline (25%)	10,870 barrels/day at $1.02/gal	465,671
Turbine jet fuel (15%)	6,522 barrels/day at $1.00/gal	273,024
Diesel fuel (15%)	6,522 barrels/day at $0.98/gal	268,446
Catalyst cracker feedstock (22%)	9,565 barrels/day at $0.96/gal	385,661
Asphalt (23%)	10,000 barrels/day at $140.00/ton	250,000
Total	43,479 barrels/day	1,643,702
Operating expenses		−103,514
Net available to pay for crude		1,540,188[a]
Crude cost		−1,457,250[b]
Before-tax profit or loss		82,938[c]

Note: Investment, $52,163,600; capacity, 43,500 barrels/day.
[a]$35.41/barrel.
[b]$33.50/barrel.
[c]$1.91/barrel.

jet fuel, diesel fuel, and other products. As can be seen, in addition to this yield of various products, this refinery produces 10,000 barrels per day of asphalt (23 percent of the crude) valued at $140 per ton or $25 per barrel; gasoline sells for $1.02 per gallon, diesel fuel for $0.98 per gallon. On a daily basis this refinery generates revenue of $1,643,702. After operating expenses of $103,514 per day have been deducted, the net amount available to pay for the crude is $1.5 million. Dividing this amount by 43,479 barrels per day yields $35.41, which is the amount available per barrel. The crude costs $33.50 per barrel, so this refinery, on a before-tax basis, is making about $2 per barrel, covering costs, and making some money.

The economic effect on this refinery when a 10,000-barrel-a-day coker is installed to convert the asphalt into lighter products is presented in Table 3. Again, a large investment of $30 million is needed; this equipment is not inexpensive. The refiner produces the range of products shown in Table

TABLE 3 Case 1: Typical Refinery Economics with Addition of Coker

Item	Unit Amount and Price	Amount ($)
Products		
Fuel gas (5.2%)	520 barrels/day at $25.00/barrel	13,000
Light ends and gasoline (17.5%)	1,750 barrels/day at $0.96/gal	70,560
Blend oil (10.5%)	1,050 barrels/day at $0.98/gal	43,218
Catalyst feed (52.0%)	5,200 barrels/day at $0.96/gal	209,664
Coke (27.0%)	2,700 barrels/day at $60.00/ton	27,000
Total		363,442
Operating expenses		−51,400
Net available to pay for feedstock		312,042[a]
Feedstock cost		−250,000[b]
Before-tax profit or loss		62,042[c]

Note: Data are for 10,000-barrel/day delayed coker; investment, $30 million.
[a]$31.20/barrel.
[b]$25.00/barrel.
[c]$6.20/barrel.

3, resulting in income of $363,442. Operating costs for this little coker are $51,400 per day, which leaves $312,042 to pay for feedstock, or $31 per barrel. Again, the feedstock cost was equivalent to the value of the asphalt that this refinery was selling for $140 per ton or $25 per barrel. Therefore, on that portion of the asphalt for which the costs were barely covered, the refinery is now making $6.20 per barrel more. Therefore, refinery operators say, why sell asphalt at $140 per ton if the asphalt can be upgraded to produce these products and bring that much more profit? The answer is obvious in this particular case. Again, all cases are not quite so simple and every refinery is different, depending on changes in product prices and crude prices.

Case 2

Actually, the economics in Case 2 may be more current than that for Case 1. The problem is the same: Asphalt is a loser. In Case 2, crude is delivered to the refinery at $29.50 per barrel, which is about $4 per barrel lower than in Case 1. In this case asphalt cement is selling for about $150 per ton, a little higher than in Case 1. The loss per barrel is $2.70 versus $7.92 in Case 1; the lower crude costs and the slightly higher asphalt sales price improve the situation significantly.

In Table 4 the specifics of the value of the light products are given; note that motor gasoline sells for $0.82 per gallon compared with $1.02 in

TABLE 4 Case 2: Typical Refinery Economics

Item	Unit Amount and Price	Amount ($)
Products		
Motor gasoline (25%)	10,870 barrels/day at $0.82/gal	374,363
Turbine jet fuel (15%)	6,522 barrels/day at $0.87/gal	238,314
Diesel fuel (15%)	6,522 barrels/day at $0.75/gal	205,443
Catalyst cracker feedstock (22%)	9,565 barrels/day at $0.79/gal	317,367
Asphalt (23%)	10,000 barrels/day at $150.00/ton	27,000
Total	43,479 barrels/day	1,403,487
Operating expenses		−103,514
Net available to pay for crude		1,299,973[a]
Crude cost		−1,283,250[b]
Before-tax profit or loss		16,723[c]

Note: Investment, $52,173,600; capacity, 43,500 barrels/day.
[a]$29.88/barrel.
[b]$29.50/barrel.
[c]$0.38/barrel.

Case 1. This price is probably more typical of what is happening locally, where gasoline pump prices are about $0.96 per gallon. As before, the revenue from the range of products plus asphalt at $150 per ton totals $1.4 million daily. Again daily operating costs are $103,514, which are deducted from the daily revenue to give a net amount for crude of $1.3 million or $29.88 per barrel. The crude cost mentioned was $19.50 per barrel; therefore, this operation is making $0.38 per barrel on a daily basis. This is less than the refiner in Case 1, who was marginally successful, made. The refiner in Case 2 is barely able to break even.

The effect of adding a coker in this case to convert the 10,000 barrels per day of asphalt into light products is presented in Table 5. Again, $30 million is invested. The same operating costs of $51,400 apply, which gives $24.42 per barrel to pay for the feedstock. In this case, the feedstock was $150 per ton or $26.80 per barrel. Therefore, in this particular case, the refinery operator decides not to spend $30 million on a coker and to continue to market the asphalt, which will yield a higher value than if it were converted to light products. In today's environment, this is probably a more realistic situation than Case 1. Cokers do not appear to be as attractive as they were when they were designed or even when they were first put into operation 2 to 5 years ago. Again, the situation may change dramatically and the original economics may have to be discarded. The purpose of this discussion has been to explain the range of alternatives that exists for a refinery and to explain how decisions may be made regarding one method of operation versus another.

TABLE 5 Case 2: Typical Refinery Economics with Addition of Coker

Item	Unit Amount and Price	Amount ($)
Products		
Fuel gas (5.2%)	520 barrels/day at $25.00/barrel	13,000
Light ends and gasoline (17.5%)	1,750 barrels/day at $0.77/barrel	56,595
Blend oil (10.5%)	1,050 barrels/day at $0.83/gal	36,603
Catalyst feed (52.0%)	5,200 barrels/day at $0.79/gal	172,536
Coke (27.0%)	2,700 barrels/day at $35.00/ton	16,875
Total		295,609
Operating expenses		−51,400
Net available to pay for feedstock		244,209[a]
Feedstock cost		−268,000[b]
Before-tax profit or loss		−23,791[c]

Note: Data are for 10,000-barrel/day delayed coker; investment, $30 million.
[a]$24.42/barrel.
[b]$26.80/barrel.
[c]$2.38/barrel.

SUMMARY

The data in Tables 2-5 show that the refiner can make more money refining crude to make asphalt under the following conditions:

1. Crude costs are low ($28 to $31 per barrel),
2. Asphalt prices are high ($150 per ton), and
3. Gasoline, jet, and turbine fuels are low ($0.75 to $0.87 per gallon). (The foregoing are refinery costs, not pump prices.)

Conversely, not making asphalt but converting it to light products is profitable under the following conditions:

1. Crude costs are high ($33 to $34 per barrel),
2. Asphalt prices are low ($140 per ton), and
3. Gasoline, jet, and turbine fuels are high ($0.96 to $1.02 per gallon). (The foregoing are refinery costs, not pump prices.)

Although each refinery is unique, the basic economics to stay in the asphalt business is as follows:

1. Asphalt must recover at least the costs of the crudes.
2. Asphalt is a valuable refinery resource; it is no longer a waste product.
3. In modern refineries, asphalt competes with light products, and the economics is determined by the selling price of all products produced.
4. A uniform, consistent, long-range highway program without drastic swings in demand for asphalt is beneficial to both users and producers. It permits refiners to plan.

Asphalt prices have not equalled crude costs in the past and they are not equal to crude costs now, and that is part of the problem. Asphalt prices must go up in order for the product to carry its own weight. Refinery operations need to recover crude costs from asphalt or more of them are going to cease asphalt production in the future. Strong light-product prices and low asphalt-cement prices have stimulated the interest in alternative manufacturing methods such as cokers, which produce no asphalt. As long as low asphalt prices continue, asphalt availability is going to be a problem because refineries would rather convert the bottoms to lighter products and generate higher revenue.

Refinery economics is changing, and cokers will not appear as attractive when asphalt demand and prices are high and gasoline prices are low. On the assumption that there will be a reasonably strong asphalt-cement demand in the future, and that as a result the prices should improve, it is expected that industry will be assured of an adequate supply of asphalt cement to meet the needs of this country's road programs.

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