Technical Paper T-127

MILLING AND RECYCLING

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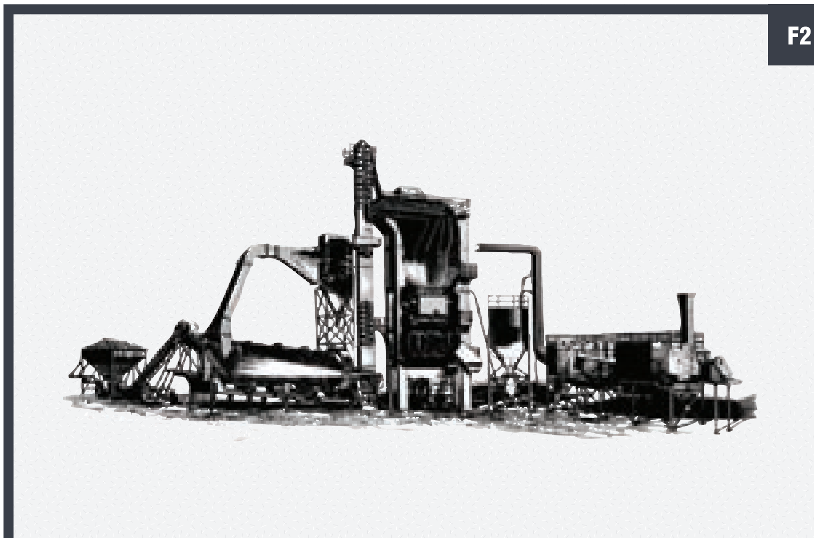
1912 Warren Brothers Plant



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Batch Plant - One Bin Cold Feed

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Rejected Aggregate

I. INTRODUCTION

As roads began to be paved with asphalt at the turn of the last century, asphalt plants were developed utilizing the tools that were available at that time. The plant shown in **Fig. 1** is a 1912 Warren Brothers plant utilizing two horses to turn a rotary table, which then turns the rotary drum of the plant through belting and gears. On the right hand end of the drum the aggregate was dried, and on the left end the aggregate was mixed with liquid asphalt brought in from Trinidad Lake. The aggregate was a “crusher run” type material, where rock was run through a crusher and all of the aggregate below a certain top size was used to make asphalt. This material tended to segregate and did not support heavy loads because of the large amount of fine material usually left in the aggregate. In time, Batch Plants were developed as shown in **Fig. 2.** This crusher run material was placed in a single feeder bin, fed through a rotary dryer, up a vertical elevator and over a screen that separated the aggregate into four sizes. Early Batch Plants used rotary screens. As vibrating equipment improved in technology, horizontal and incline vibratory screens were developed for plant use.

To achieve the combination of gradations desired by the mix designer one size of a particular material was often rejected as shown in **Fig. 3.** Since the material had been dried prior to screening and then not used, this resulted in a lot of waste product and wasted energy. This led aggregate producers to begin producing multiple sizes, and multiple feeder bins were placed on the batch plant as shown in **Fig. 4** so the material did not have to be rejected. By the late '60’s and early '70’s, gradations from the aggregate producers were consistent enough that continuous mix plants became more prevalent, leading to the more modern continuous plants with multiple storage bins as shown in **Fig. 5** today. The use of recycle, or Reclaimed Asphalt Pavement (RAP), in the HMA industry began in the early part of the twentieth century when pavements were made from Trinidad Lake Asphalt. This asphalt was naturally found in the “Lake” in Trinidad, West Indies. Because of the high price of liquid asphalt at that time, producers remelted hot mix from city streets and incorporated this recycle material into new mixes.

After oil was discovered in Pennsylvania and Texas, the price of liquid asphalt dropped because it was a waste residue from the oil refining process. As a result, the cost of new liquid asphalt and aggregate was less than the cost of removing and processing the RAP. In the 1970's, two things occurred: oil prices escalated and milling machines were developed to easily remove old pavement surfaces. This made the use of recycle economically feasible again. RAP is even more economical today as the prices of liquid asphalt and aggregate continue to increase.

Over the past thirty years, the price of liquid asphalt has fluctuated between $80 per ton and $300 per ton. Additionally, aggregate has continued to become more expensive since aggregate reserves have been depleted in many areas. Because it is worth the material it replaces, the value of RAP fluctuates with the price of virgin material. In the foreseeable future, it seems unlikely that cheap asphalt and aggregate will ever return. As the prices of both materials increase, recycle becomes more valuable.

The availability of RAP varies based on the location of the asphalt plant. In metropolitan areas where milling and inlay paving are commonplace, contractors often mill more RAP than they can consume. Contractors therefore look for places to send this excess recycle, such as rural areas where RAP is not as readily available.

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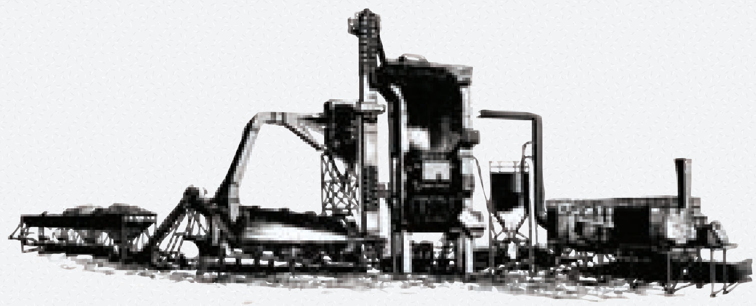

Batch Plant - Four Bin Cold Feed

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Modern, Continuous Mix Facility

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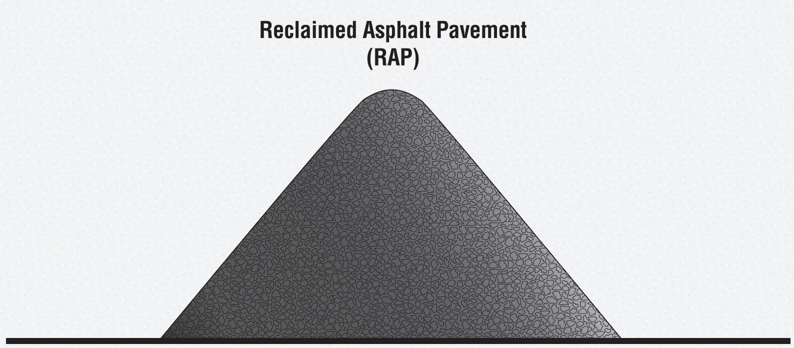
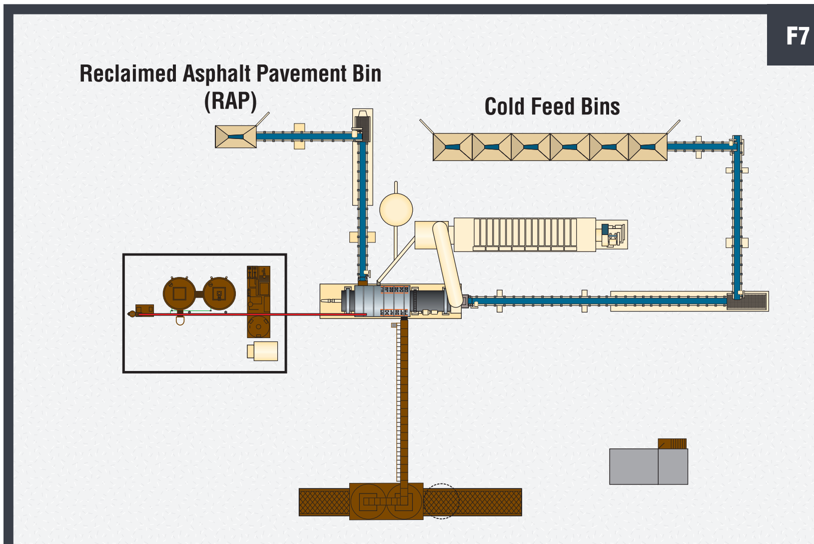
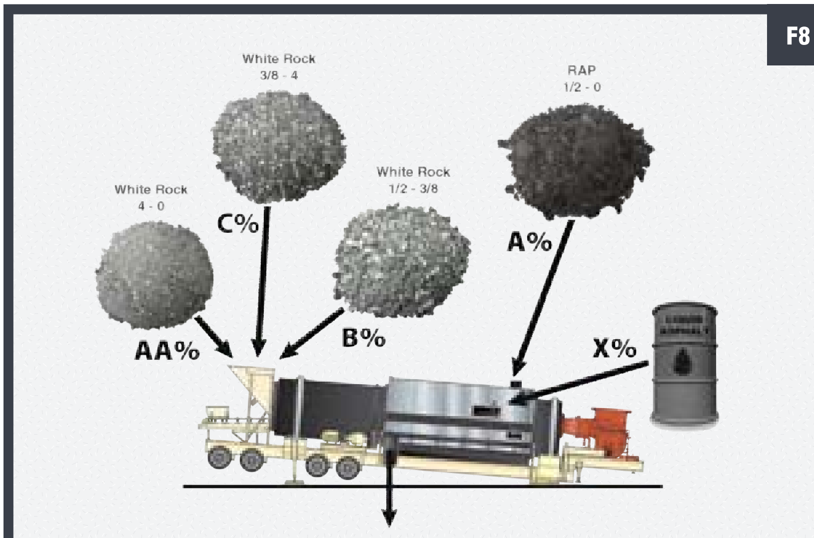


RAP Pile With 1/2" Minus to 3/4" Minus Aggregate



1980-1990's HMA Facility with Single RAP Bin



Superpave Mix With 1/2 RAP

Rutting Often Occurs in Older Overlay Pavements

Because recycle percentages in HMA will continue to increase, producers looking to purchase a new plant should be careful to acquire equipment that will be able to consume high percentages of RAP (up to 50%) without using substantially more fuel.

Over the next twenty years, the amount of recycle will most likely increase in every area of the country. Rural areas will become urban centers, and little new construction will occur in existing metropolitan areas. Generally speaking, the majority of the roadwork will be milled and inlayed, and these projects will generate enough RAP to produce mixes made from 100% recycle material. Since 50% RAP seems to be the current practical limit for HMA producers, disposing of the excess recycle material will become a problem. Only producers who can utilize high percentages of RAP will be competitive in this market.

Mix designs in the 1980's and early 1990's were not as specific as they are today, and producers did not have to closely monitor gradation and asphalt content. But today, with the new Superpave mix design procedure and emphasis on pavement quality, the amount of recycle is often limited to 20%, unless the RAP is further processed.

As Hot Mix Asphalt (HMA) was milled off the roads, it was generally piled up and treated as a black crusher run as shown in **Fig. 6.** Since only low amounts were added to the mix this material was fed in a single aggregate bin as shown in **Fig. 7.** While the virgin material was sized in as many as four to six sizes, the recycle was treated again like a black crusher run as shown in **Fig. 8.**

Over the history of the use of Hot Mix Asphalt for pavements, many different mix design procedures have been used and the loads and traffic volume that the roads are subjected to have changed substantially. As a result, many roads developed rutting due to having too many fines as shown in **Fig. 9.** Poor construction techniques were used over the years where mix was replaced with center line segregation as shown in **Fig. 10** and **Fig. 11.** Poor bases were used as shown in **Fig. 12** and end of load segregation occurred as

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Center Line Segregation

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Center Line Segregation

F12

Poor Base Line Reduces Road Life

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End of Road Segregation

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Rock Quarry

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Oil Well

shown in **Fig. 13.** This led mix design engineers to look at the older recycle pavement as being an inferior or less valuable material.

As mentioned earlier, the Superpave Mix design procedure was developed in the late '80's and implemented in the '90's, it made it very difficult to put more than 20% recycle into mixes and maintain the proper volumetric requirements. Basically, the Superpave Mix design procedure requires very close control of the gradation of the incoming aggregate. Since the recycle was treated like a black crusher run it tended to segregate, making it nearly impossible to control the asphalt content and volumetrics as the amount of recycle was increased above 20%.

As prices have increased substantially in the last two to three years and shortages have occurred in both liquid asphalt and aggregates, this has lead the industry to re-evaluate the use of recycle mixes, particularly the use of it in higher quantities.

Doing a more thorough analysis, we see that rock in recycle is the same age as the aggregate **(Fig. 14)** coming from the rock quarry today and the same age as the liquid asphalt coming from the refined oil from the oil well **(Fig. 15).** If we process the recycled asphalt pavement by taking it apart and reducing it to its original ingredients as shown in **Fig. 16,** then we produce exactly the same products that we are using today in aggregate gradation as the virgin aggregate; although that product has a film of asphalt already present on it. By crushing and screening the material as shown in **Fig. 17,** we can separate it and this will allow us to recombine the material into an engineered mix as shown in **Fig. 18.** Pavements today must perform under different loads and different traffic conditions than in the past. This may require pavements to be built with aggregates that are less prone to polish. The skid numbers for aggregates are not measured on materials less than 1/4-inch in diameter. As shown in **Fig. 18,** combining the minus 1/4-inch or smaller recycle with the coarser skid resistant white rock, we could utilize a substantial amount of the recycle and meet the requirements demanded today. As the recycled material is separated, it should be noted that the amount of liquid available is substantially higher in the finer aggregates than in the coarser aggregates. If recycled asphalt that originally had 6% liquid in it is separated, generally, the 4 x 0 will contain 7 to 7½% liquid while the 3/8 x 4 may contain as little as 4% and the 3/8 x 1/2-inch will contain as little as 3% liquid asphalt.

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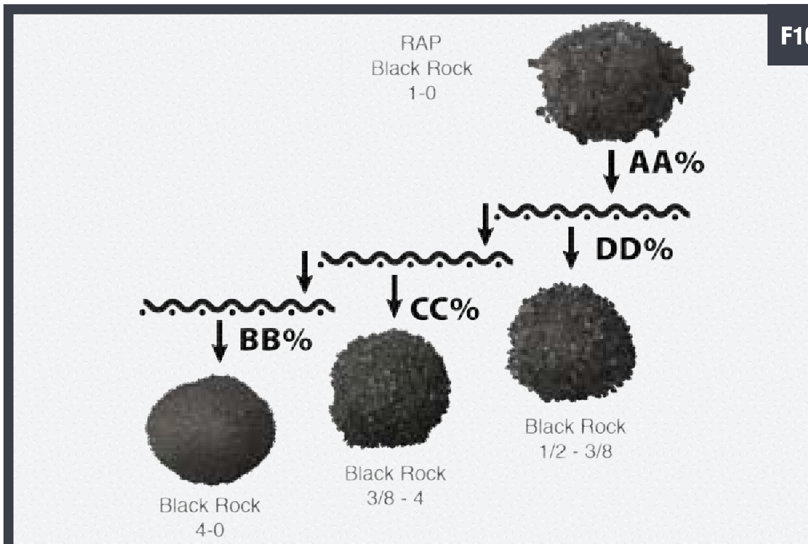

Processed RAP Screened To Original Ingredients

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RAP Can Be Crushed and Screened Like Virgin

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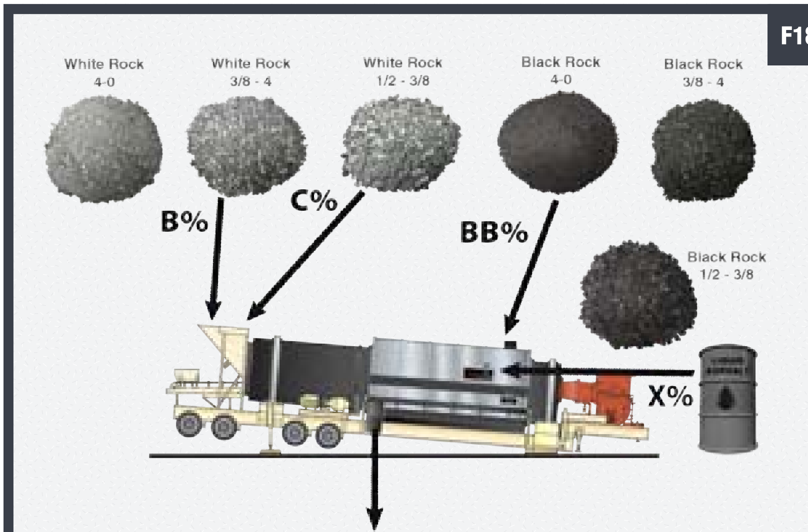
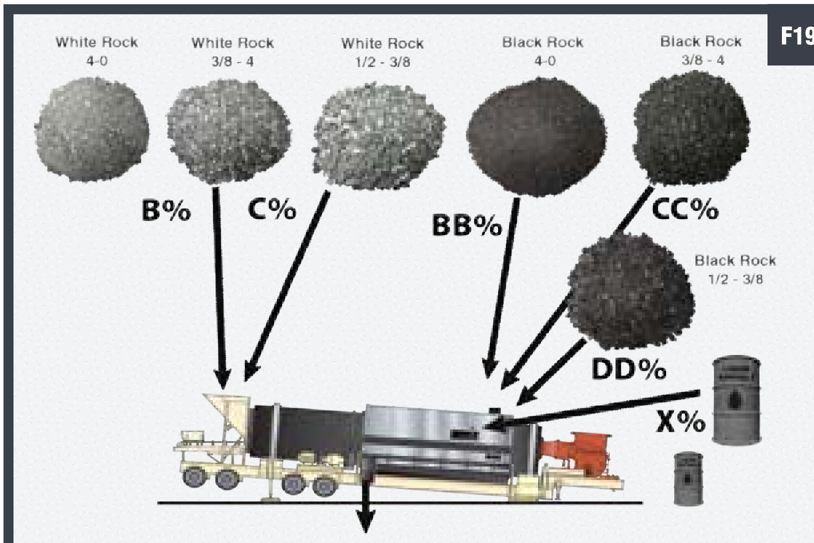


Superpave Mix With Processed RAP - Choice #1



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Superpave Mix With Processed RAP - Choice #2

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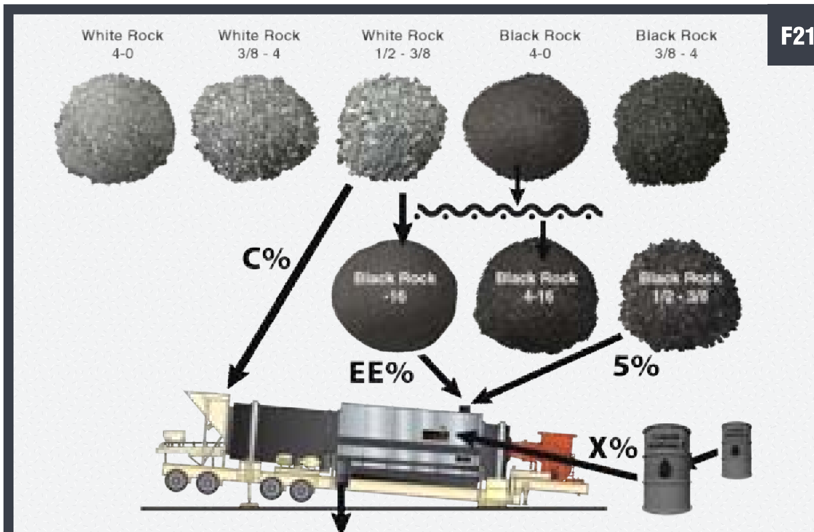
Processing RAP Through 1/2 Minus Screen



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Superpave Mix With Processed RAP - Choice #3

When all of the sizes of the recycled material are used as shown in **Fig. 19,** separating it eliminates the segregation of the material and allows the injection of recycle up to 50% without experiencing volumetric variations.

Since most of the recycle is coming from milled material which is generally surface mix, 90% of the recycle processed today is ½-inch minus. When processing through a ½ size screen as shown in **Fig. 20,** generally two to three separations can be made with 70% of the material going through the ½-inch screen. This then only requires the crushing of the separated oversize material. It should be noted that we actually do not want to crush the material, but just take it back apart.

The newer SMA or interlocking stone type mixes perform extremely well but are more expensive than the more uniformly graded mixes. As shown in **Fig. 21** by separating the 4 x 0 even further, RAP can be utilized as a black filler in the SMA mix. The remaining product is a 4 x 16, which is a black manufactured sand and can be used in practically any mix. Likewise, the 1/2 x 3/8 black material can reduce the amount of white aggregate required, further reducing the cost of the mix. The minus 16 mesh material generally will contain from 9 to 10% recycle. The combination of these will allow the production of an excellent SMA mix with a cost compatible to that of a dense graded mix. As shown in **Fig. 19** and **Fig. 21** depending on the hardness of the recycled asphalt, fluxing agents or softer materials may be a required addition to the new liquid to offset the hardness of the older asphalt. By utilizing two metering systems as shown in **Fig. 22,** fluxing material or softer liquids can be blended together on the fly and a viscosity meter installed in the asphalt line allowing the production of higher percentages of recycle; automatically varying the asphalt viscosity to match the differences in recycle percentages.

Many people associate the term "recycle" with material that is not as good as new, second-rate, or considered to be poor quality used material. Due to this misconception, Reclaimed Asphalt Pavement, or RAP, has been treated like a waste product. Little time or money has been spent to process RAP since it is not considered to be valuable. In reality, any recycle product is worth what it replaces, and its value can be enhanced, if the material is processed and treated like virgin material. Because it can be processed and used to replace virgin aggregate and liquid asphalt, there is great value in "recycle" as the term relates to Hot Mix Asphalt (HMA) materials.

The largest quantity of RAP comes from milling operations. Most often, the original surface mix is made of 1/2-inch aggregate, and since most mixes are made of 1/2-inch or larger rock, operators generally crush all RAP to 1/2-inch minus.

A pile of RAP crushed to 1/2-inch minus is like a black "crusher run" aggregate product and it can only substitute in a mix for the same or larger size aggregate. In this case, due to segregation and tight control of air voids in the finished product, RAP content is generally limited to 20% or less.

If we could take a pile of RAP and physically extract the liquid asphalt and then screen the aggregate into three piles of clean rock, a 30,000 ton pile of RAP with 6% liquid asphalt would produce approximately 28,200 tons of clean aggregate plus 420,000 gallons of liquid asphalt, enough liquid to fill 70 transport trailers **(Fig. 23).** Considered in these terms, RAP has significant value and is no longer considered a second-rate material.

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Two Metering Systems

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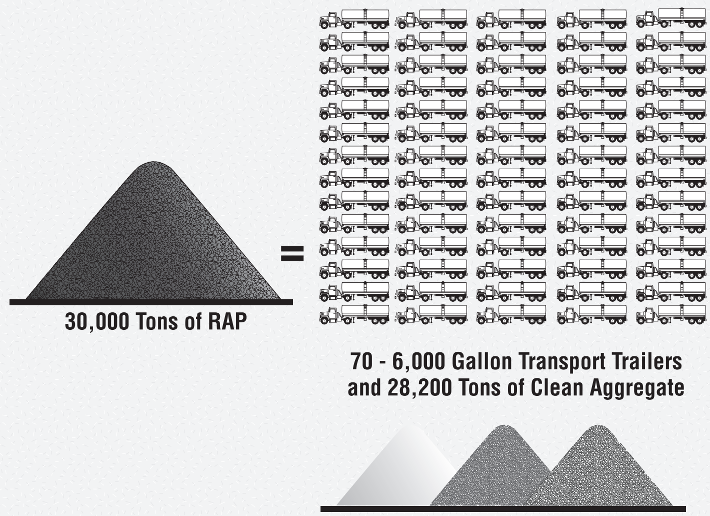

RAP is Worth the Virgin Material It Replaces

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Virgin Aggregate (per ton) .... $10 x 0.94 = $ 9.40
Liquid Asphalt (per ton) .... $350 x 0.06 = $21.00
$30.40

RAP Milling Cost (in job) .... $ 0
Total Cost of RAP (per ton) ....$ 3.40
Difference $27.00

10% RAP $2.70/ton	10 tons mix	
20% RAP $5.40/ton	5 tons mix	
50% RAP $13.50/ton	2 tons mix	

Savings: Virgin Materials vs. RAP (if RAP at no cost)

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Virgin Aggregate (per ton)	$10 x 0.95 =	$ 9.50
Liquid Asphalt (per ton)	$350 x 0.05 =	$17.50
		$27.00
Cost of RAP (per ton)	$ 2.00	
Crushing Cost (per ton)	$ 3.00	
Total Cost of RAP (per ton)	$ 5.00	$ 5.00
	Difference	$22.00

10% RAP	$1.45/ton	10 tons mix
20% RAP	$2.90/ton	5 tons mix
50% RAP	$7.25/ton	2 tons mix

Savings: Virgin Materials vs. RAP (if RAP is purchased)

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RAP Crushing Plant

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Breaker System

To calculate the intrinsic value of RAP, the cost of the virgin mix must be determined. For example, if the cost of aggregate is $10 per ton and the cost of liquid asphalt is $350 per ton, then a mix using 6% liquid asphalt would have a material cost of $30.40 per ton, as shown in **Fig. 24**. If this material was available from a job at no cost to the producer, and it cost $3.40 per ton to truck it to the plant and process it to match the gradation of virgin aggregate, then a portion of the mix materials could be replaced with the less expensive RAP. When running a mix with 20% recycle material, the producer would save $5.40 per ton. When running 20% recycle, one ton of RAP could be distributed into five tons of new mix, resulting in a total savings of $27 per ton of RAP consumed.

Fig. 25 shows the savings at various RAP contents, when paying $2 per ton to obtain RAP with 5% liquid asphalt and spending $3 per ton to crush the RAP, this producer would save $22.00 per ton of RAP used.

This example shows that as virgin material costs rise, recycle becomes more valuable. The value of RAP is the same as the material it replaces. But to realize the full value of RAP, producers must treat it like virgin aggregate. It must be milled from the roads, processed (resized) using the same techniques used for virgin aggregate, then sent through the asphalt facility where it is dried, heated, remelted, and mixed with virgin materials to make a uniform asphalt product.

II. OBTAINING AND PROCESSING RAP

Approximately 600 million tons of Hot Mix Asphalt (HMA) are produced in America each year. In relation to our current population, this equals approximately 2 to 2.5 tons of mix per person per year. Industry sources also estimate that America's roads have in place 18 to 20 billion tons of asphalt stretching over 2.3 million miles. Many of these surfaces are in need of repair, and the asphalt must be removed to correct deformities. The removal of these surfaces generates a valuable resource for HMA producers: Reclaimed Asphalt Pavement (RAP).

RAP can be removed from existing roadways using one of two basic methods. The pavement can be broken and "ripped" up, or it can be milled.

When ripping up pavement, RAP must then be processed through a crushing plant. Impactor crushers, as shown in **Fig. 26**, can be fed by loaders or excavators.

Horizontal shaft impactors are high reduction machines and are very suitable for crushing RAP. When processing RAP, the size of the opening on the crusher is more important than the tons per hour it can produce. For larger openings, larger crushers have to be used, resulting in a higher initial cost. But the ability to digest large chunks of RAP on a continuous basis without having to pre-size the material makes the larger machine worth the initial investment.

When crushing ripped RAP, it is advisable to use either a breaker mounted on the feeder **(Fig. 27)** or a guillotine in the inlet of the crusher **(Fig. 28).** Both pieces of equipment break the oversized material, reducing stoppages of the crusher. This allows the operation to be more continuous and therefore produce a more consistent RAP product. After the recycle leaves the impactor, it must be screened and separated into different material sizes and stockpiled **(Fig. 29).**

Unless the entire thickness of roadway is being removed, milling the road is far superior to ripping it up because of the condition in which this process leaves both the roadway and the RAP. By milling each individual layer of pavement from the road, material of differing qualities can be kept

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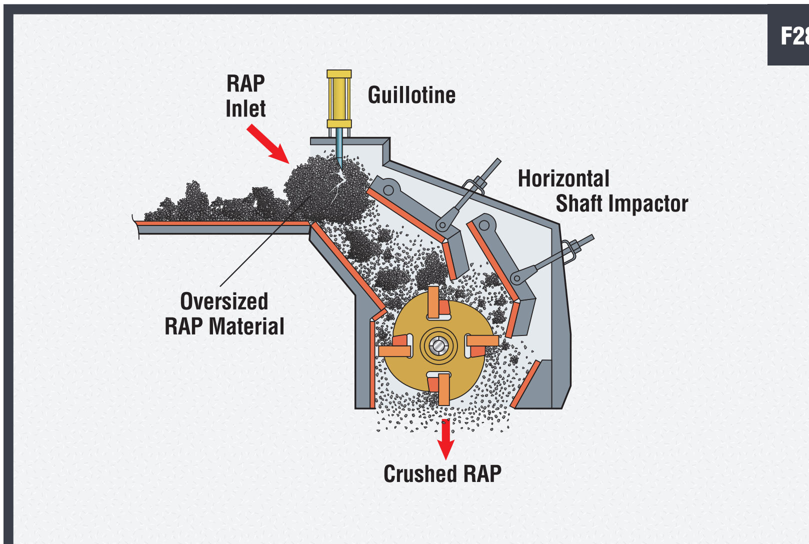

Horizontal Shaft Impactor with Guillotine

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Screening Plant Producing Two RAP Products

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1970's Half-Lane Milling Machine

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Today's Half-Lane Machine

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1"	Operating Cost per Hour	$315.00
	Production Rate (sq yd/hr)	1250
	Production Rate (ton/hr)	70
	Total Cost per Square Yard	$ 0.25
	Total Cost per Ton	$ 4.56
2"	Operating Cost per Hour	$320.00
	Production Rate (sq yd/hr)	870
	Production Rate (ton/hr)	90
	Total Cost per Square Yard	$ 0.37
	Total Cost per Ton	$ 3.56
3"	Operating Cost per Hour	$345.00
	Production Rate (sq yd/hr)	700
	Production Rate (ton/hr)	110
	Total Cost per Square Yard	$ 0.49
	Total Cost per Ton	$ 3.14
4"	Operating Cost per Hour	$390.00
	Production Rate (sq yd/hr)	600
	Production Rate (ton/hr)	125
	Total Cost per Square Yard	$ 0.65
	Total Cost per Ton	$ 3.12

Based on using a BG RX-40 or CMI PR 450 (1970's vintage) half-lane milling machine that operates 750 hr/yr. Costs not adjusted for inflation.

Half-Lane Milling Costs in the Early 1970's

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		HIGH*	LOW**
1"	Operating Cost per Hour	$385.00	$332.00
	Production Rate (sq yd/hr)	3143	3600
	Production Rate (ton/hr)	170	200
	Total Cost per Square Yard	$ 0.12	$ 0.09
	Total Cost per Ton	$ 2.26	$ 1.66
2"	Operating Cost per Hour	$395.00	$340.00
	Production Rate (sq yd/hr)	2461	3030
	Production Rate (ton/hr)	272	334
	Total Cost per Square Yard	$ 0.16	$ 0.11
	Total Cost per Ton	$ 1.45	$ 1.02
3"	Operating Cost per Hour	$405.00	$349.00
	Production Rate (sq yd/hr)	2083	2651
	Production Rate (ton/hr)	345	439
	Total Cost per Square Yard	$ 0.19	$ 0.13
	Total Cost per Ton	$ 1.17	$ 0.79
4"	Operating Cost per Hour	$415.00	$357.00
	Production Rate (sq yd/hr)	1893	2272
	Production Rate (ton/hr)	410	502
	Total Cost per Square Yard	$ 0.22	$ 0.16
	Total Cost per Ton	$ 1.01	$ 0.71

Based on using a Roadtec RX-700 half-lane milling machine with a 7'2" drum and housing that operates 750 hr/yr and uses fuel costing $3.00 per gallon.
***HIGH refers to high labor costs and abrasive aggregate (granite)**
**** LOW refers to low labor costs and soft aggregate (limestone)**

Half-Lane Milling Costs Today

separate. In addition, milling offers the opportunity to significantly improve the surface smoothness of the milled pavement, often eliminating the need for additional preparation before paving.

Milling machines, also called pavement profilers, were first available in the mid-1970's. **Fig. 30** shows a typical half-lane, rear-load milling machine of the 1970's. Today's milling machines like the front-load model shown in **Fig. 31** are more productive and versatile than the early machines, as a result, the cost of milling has been significantly reduced.

Early machines were expensive to operate due to high maintenance and tooth replacement costs. In addition, these machines were often unreliable. The milling cost on these early machines was between $3 and $5 per ton in the 1970's **(Fig. 32)**. With inflation, the milling cost using these machines today would be $9 to $15 per ton.

Since the 1970's milling machines have grown in size, horsepower, and capacity. Innovations have also been made to significantly improve the design, construction, and mounting of milling teeth. Today, the average cost of a set of milling machine teeth is approximately $580, and today's tooth will last as long as three of the older, more expensive teeth. Longer tooth life is an important improvement that has significantly reduced the labor required to change teeth. Also, the horsepower increases over the years have improved production rates and significantly decreased costs.

Fig. 33 shows the typical cost of operating today's half-lane milling machine. **Fig. 34** shows the average cost of a full-lane milling machine. These costs vary considerably depending on the aggregate used to produce the original pavement. Very abrasive rock can result in milling costs twice as a high as that of softer aggregate. Soft aggregates therefore result in much lower operating costs. As shown in **Fig. 33** and

Fig. 34, milling with today's half-lane and full-lane machines can vary in cost from $0.63 to $2.26 per ton.*

A simple comparison of half-lane to full-lane milling costs does not accurately reflect all of the savings associated with using a full-lane machine. Because these machines can cut an entire lane in a single pass, downtime associated with backing up the machine for a second pass and the cost of adding a second machine and crew are eliminated. Only full-lane machines facilitate a true "mill and fill" operation with a single machine and crew.

Fig. 35 shows a new machine with a full-lane drum. In addition, the same tractor, or carrier, can be adapted to various paving widths depending on the width of the drum. In reality, today's milling machines should be viewed as "mining machines," since the real value is in obtaining RAP material to use in new hot mix. There are, however, many other reasons for milling with these machines, and these reasons will be discussed in the following section.

***Calculations based on using a half-lane machine with a 700 horsepower engine and seven-foot, two-inch cutting drum and a 950 horsepower full-lane machine with a twelve-foot, six-inch cutting drum. Operating costs for both types of machines include depreciation, labor costs for a three-man crew, fuel, teeth, maintenance, and repairs. Production rates based on fifty minutes of actual milling per hour of use.**

III. MILLING

Milling a road versus overlaying with new pavement offers many important benefits. Overlaying often requires additional work in raising the elevation of shoulders and utilities. Overlays also add dead weight to bridges and overpasses.

With overlays, changes in clearances and elevations of the road are required. **Fig. 36** shows how milling and inlay techniques eliminate the

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		HIGH*	LOW**
1"	Operating Cost per Hour	$498.00	$425.00
	Production Rate (sq yd/hr)	4867	5733
	Production Rate (ton/hr)	270	315
	Total Cost per Square Yard	$ 0.10	$ 0.07
	Total Cost per Ton	$ 1.84	$ 1.35
2"	Operating Cost per Hour	$510.00	$436.00
	Production Rate (sq yd/hr)	4133	4933
	Production Rate (ton/hr)	450	540
	Total Cost per Square Yard	$ 0.12	$ 0.09
	Total Cost per Ton	$ 1.13	$ 0.81
3"	Operating Cost per Hour	$522.00	$447.00
	Production Rate (sq yd/hr)	3267	4000
	Production Rate (ton/hr)	535	656
	Total Cost per Square Yard	$ 0.16	$ 0.11
	Total Cost per Ton	$ 0.98	$ 0.68
4"	Operating Cost per Hour	$535.00	$458.00
	Production Rate (sq yd/hr)	2667	3333
	Production Rate (ton/hr)	583	730
	Total Cost per Square Yard	$ 0.20	$ 0.14
	Total Cost per Ton	$ 0.92	$ 0.63

Based on using a Roadtec RX-900 full-lane milling machine with a 12'6" drum and housing that operates 750 hr/yr and uses fuel costing $3.00 per gallon.
***HIGH refers to high labor costs and abrasive aggregate (granite)**
**** LOW refers to low labor costs and soft aggregate (limestone)**

Full-Lane Milling Costs Today

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Full-Lane Milling Machine

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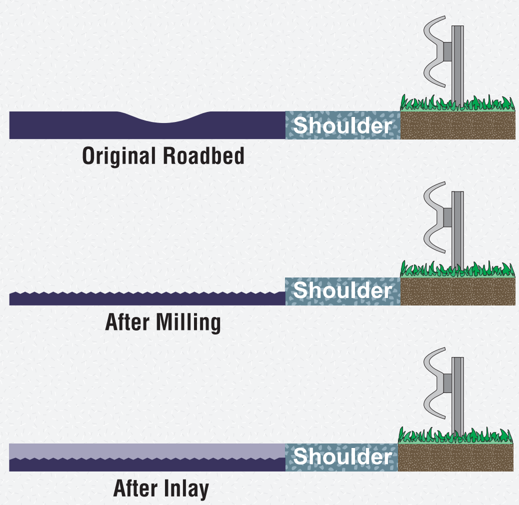

No Shoulder or Guardrail Changes with Milling

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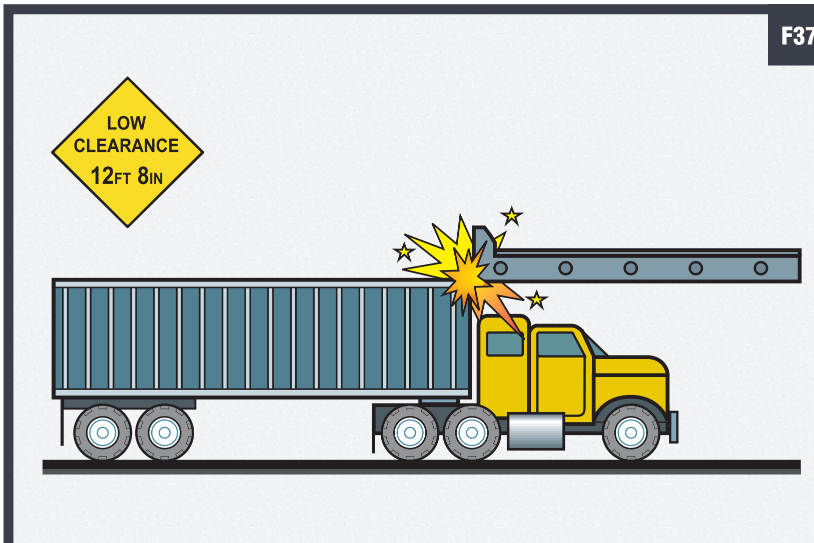

Overlays Change Bridge Clearances

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Weight Limits Remain Constant with Milling

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Multiple Overlays Create Drainage Problems

need to raise shoulders and guardrails. When the road surface is milled prior to paving, changes in bridge clearances are also eliminated **(Fig. 37).**

As new pavement surfaces are added to a bridge, additional weight is placed on the structure, reducing the net effective weight that can be transported across it. By milling the old surface and replacing it with new pavement, weight limits on bridges remain constant **(Fig. 38).**

Often, older streets have as many as four overlays, resulting in poor drainage **(Fig. 39).** By milling the older pavements, drainage can be re-established to improve water run-off **(Fig. 40)**, making the road safer for driving.

In most cities, utilities are underneath the pavement. Overlays require raising utility manholes, and this often costs as much as the new pavement. By milling and inlaying the new pavement, the elevations of existing utilities remain unchanged **(Fig. 41).**

Many of America's roadways have been affected by recent changes in demographics. In areas where the population has changed significantly, roads often consist of multiple layers of surface mix. These older layers are often structurally inadequate by today's standards, though they were strong enough to support the weight and traffic at the time they were placed. As traffic and loads have increased, rutting has occurred due to heavy loads. In these cases, the mix was not designed to support the increased weight. On interstate routes where traffic has increased significantly and multiple overlays with high fines have been placed, rutting often occurs **(Fig. 42).**

Unlike the dense graded mixes of the past, today's new mixes with interlocking stones support heavy weights without rutting. But if these new mixes

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Milling Ensures Proper Water Drainage

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Milling Leaves Utilities Unchanged

F42

Rutting Often Occurs in Older Overlay Pavements

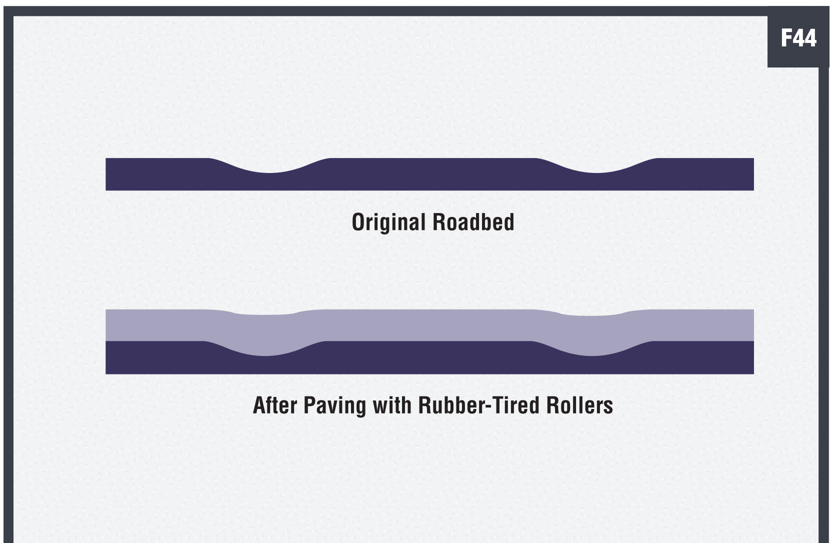
are placed over a rutted road, cracking and rutting will recur **(Fig. 43).**

If rubber-tired rollers are used to compact the new pavement, uniform density can be maintained, but the road will still become re-rutted **(Fig. 44).** Only by milling the original surface to the bottom of the ruts can a flat surface plane be established. **Fig. 45** shows how a uniform thickness of asphalt can then be applied, resulting in uniform compaction and density.

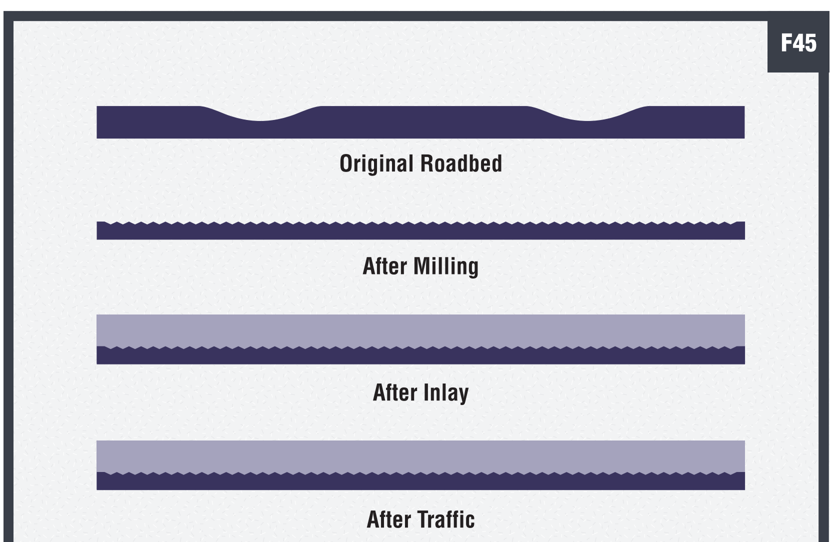
The milling technique itself also makes inlay pavements superior to overlays. Milling machines create a grooved surface, as shown in **Fig. 46.** This results in an excellent interlocking surface to interface with new pavement materials. Many states have found that the bonding between the new and old pavements is of superior quality due to the grooved surface created by milling machines. Often, the tack coat can be eliminated when placing new pavement on a properly milled and grooved surface.

Today's milling machines are available with a variety of cutter drum pattern choices. By altering cutter tooth spacing on the drum, contractors can use anything from 3/4-inch tooth spacing (excavating pattern) to 2/10-inch tooth

Overlays Can Experience Cracks and Re-Rutting



Overlays Can Cause Instant Re-Rutting



Milling and Inlays Prevent Re-Rutting

spacing (micro-milling pattern) to achieve the production and surface texture requirements that best suit their application. **Fig. 47** shows four common pattern choices: excavating, traditional, profiling and micro-milling.

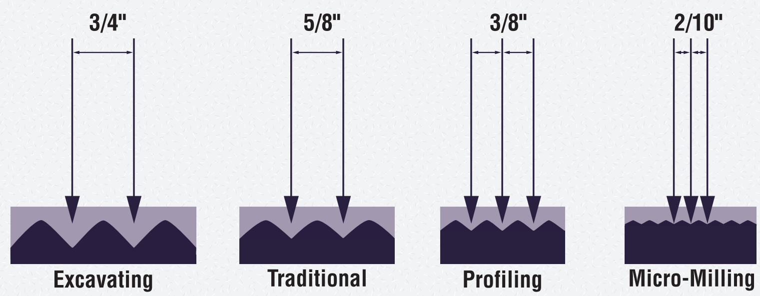
Fig. 48 shows a traditional or standard milling cutter drum with 5/8-inch spacing versus a micro-milling drum with 2/10-inch spacing. Traditional spacing works well for most applications, but micro-milling leaves a finely milled surface that can be opened up to traffic immediately. Micro-milling is typically used for cuts no deeper than one-inch. In some situations, micro-milling is used as an alternative to diamond grinding. Some cities use micro-milling to correct pavement irregularities without applying a new pavement layer.

Profiling, requiring 3/8-inch tooth spacing, is used in many states to achieve a deeper cut than possible with micro-milling without disrupting the structure of the existing roadway. The slightly tighter tooth spacing (3/8-inch vs. traditional 5/8-inch) of the profiling drum allows contractors to maintain more consistent longitudinal and horizontal leveling than can be achieved with a traditional milling

F46

Milling Creates a Grooved Surface

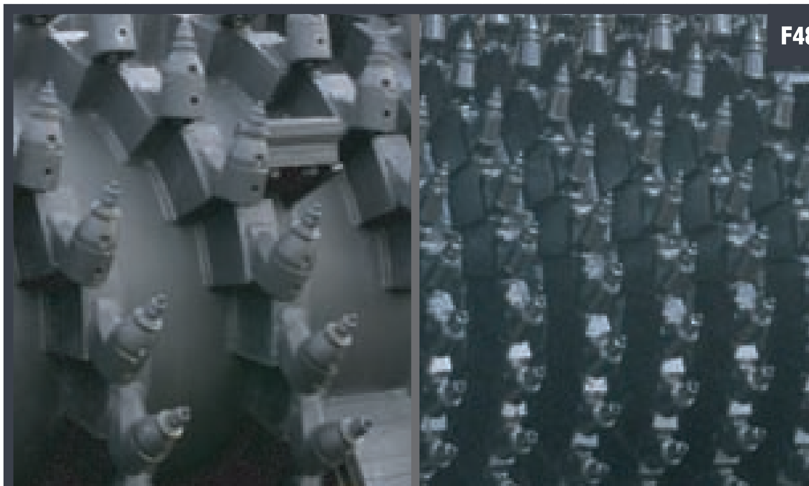
F47



Each cutter pattern is determined by the number of carbide teeth installed on the mandrel. More teeth produce fine patterns such as Profiling and Micro-Milling, but production rates remain low. Excavating and Traditional patterns allow for higher production rates but produce a coarser surface.

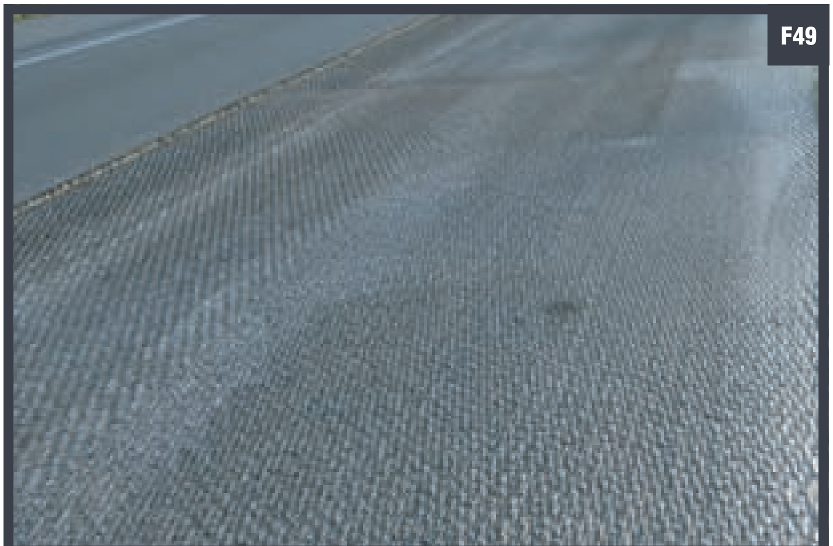
Milling Machine Cutter Drum Patterns

F48

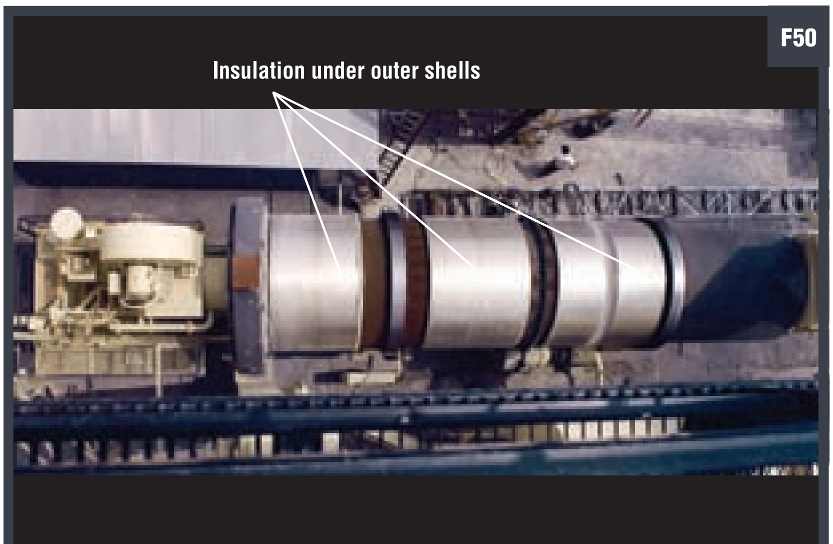


Traditional Drum | Micro-Milling Drum

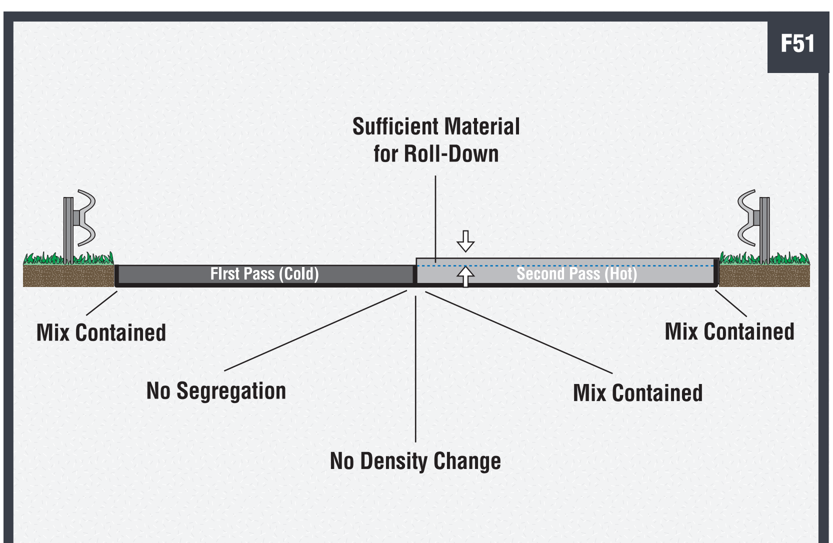
Traditional and Micro-Milling Cutter Drums



Profiled Surface



Insulated Dryer Shell



Milling Ensures Consistent Pavement Density

drum. The profiled surface shown in **Fig. 49** is smooth enough to drive on in some instances, particularly during rural county or city repaving operations, and it provides an excellent base for the new pavement surface.

On the other end of the spectrum, excavating tooth patterns are designed for projects that require substantial roadway removal such as shoulder reconstruction to combat erosion or the reconstruction of rural roads.

Today's milling machines also use extremely accurate grade and slope controls (**Fig. 50**). Milling machines can be used to level the road in both longitudinal and traverse directions. In the past, very little longitudinal leveling was done. By using current grade and slope controls, a much smoother pavement surface can result. Due to these advances, many states are now requiring smoothness measurements of milled surfaces.

Inlays offer the additional advantage of obtaining a more uniform joint density. With milling, the new pavement is confined between the two edges of the milled surface (**Fig. 51**). The density of the pavement is therefore uniform at the both the centerline and edges. With overlays, it is difficult to maintain uniform densities at the centerline joints and edges of the pavement since the mix is not confined (**Fig. 52**).

With the extremely high volumes of traffic today, road repairs are much more difficult than in the past. The public demands minimal interruptions, and the milling and inlay process greatly reduces the time to repair the road. New milling machines like the one shown in **Fig. 53** are being developed to pick up the large fines in the milled surface. This type of machine in conjunction with a transfer machine and paver (**Fig. 54**) can result in a close-coupled paving operation (**Fig. 55**). When interlocking stone mixes are used, very little compaction is required and traffic can almost immediately be returned to the pavement. With the short distance between the milling machine and paver, the mix can be hauled to the job, then the same trucks can be used to return the milled material to the asphalt plant. This type of operation results in minimal interruption for the public and reduces trucking costs due to the double-haul. These paving jobs are often done at night, further reducing the inconvenience to motorists.

When tack coats are required, the machine shown in **Fig. 56** sprays the tack coat directly in front of the auger on the paver. This is particularly effective when using a PG liquid to tack, because no curing time is required. The paving operation can be closer-coupled, and a separate tack truck is eliminated. No additional cleaning is required behind the milling machine since the trucks, paver, and transfer machine do not travel on the tack coat.

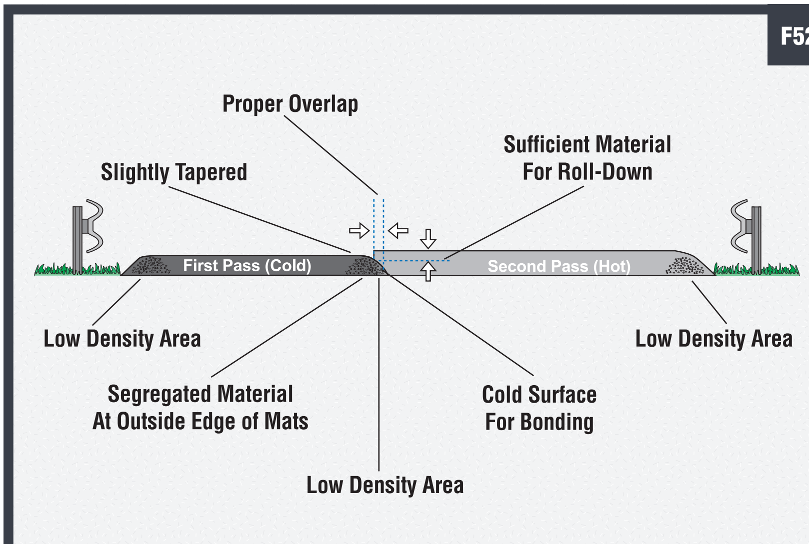
Recent advances in milling and paving machines make close-coupled paving operations more feasible. These advances eliminate joint problems resulting in a longer life of the roadway, and they minimize disruptions to the public.

IV. CONVERTING RAP TO HMA

Because processing techniques have been refined and higher percentages of recycle are commonly used in mixes, plant equipment must be able to cleanly and efficiently produce the mixes. The amount of RAP, the type of plant, and the equipment configuration can affect production capacities, plant operating costs, and the quality of the mix.

As RAP percentages increase, the required amount of front-end preparation and type of plant equipment needed will also change. The following five stages of RAP injection show the changing equipment needs that accompany increases in RAP percentages.

F52



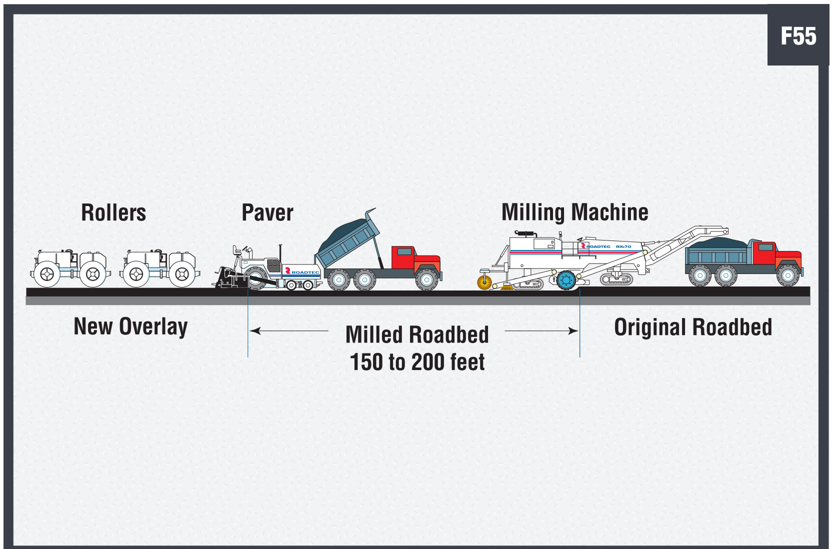
Overlays Create Inconsistent Pavement Densities

F53

Today's Machines Mill and Pick Up Fines

F54

Material Transfer Vehicle and Paver



Close-Coupled Paving Operation

Roadtec's Spray Paver™ Applies Tack Coat

Continuous Mix HMA Facility

Stage One—0 to 10% RAP

When producing mixes using between 0 and 10% recycle, the percentage of RAP is so low that it has little effect on the aggregate gradation and asphalt content in the mix. When fed into a continuous mix asphalt facility (**Fig. 57**) or a batch plant (**Fig. 58**), RAP should be a milled or crushed material that is conveyed over an appropriate scalping screen to prevent oversized material from entering the mix. When using amounts as low as 10% recycle, operators have also successfully fed

RAP into batch plants on a continuous basis using a bucket elevator.

Many continuous plants include a closed-circuit crushing arrangement as shown in **Fig. 59**. The oversized material is crushed and returned to the screen so that all of the product will pass through the scalping screen prior to entering the asphalt plant. This is particularly effective when processing milled material.

Low percentages of recycle can effectively be run through a parallel flow drum mixer (**Fig. 60**), parallel

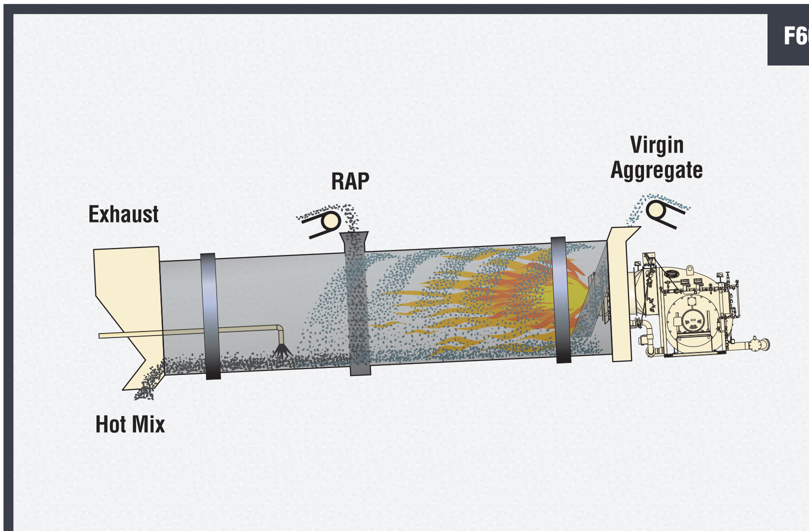
F58

HMA Batch Facility

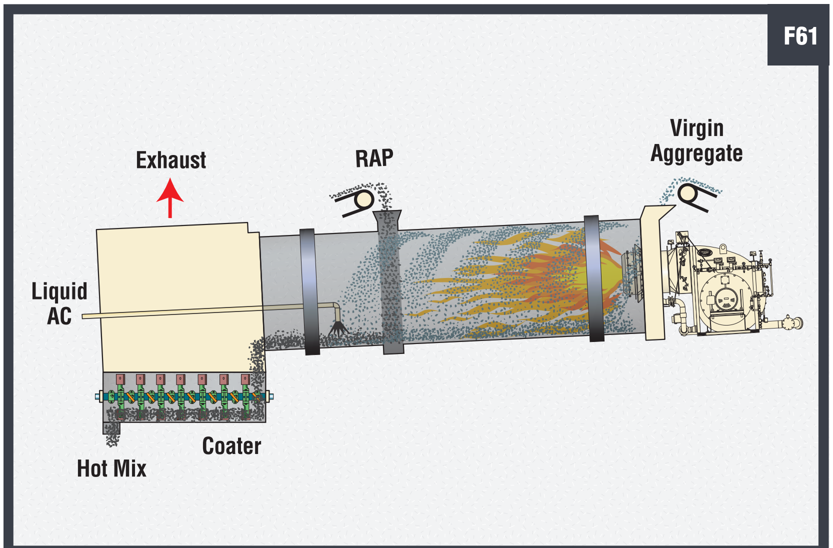
F59

Closed-Circuit Crushing System

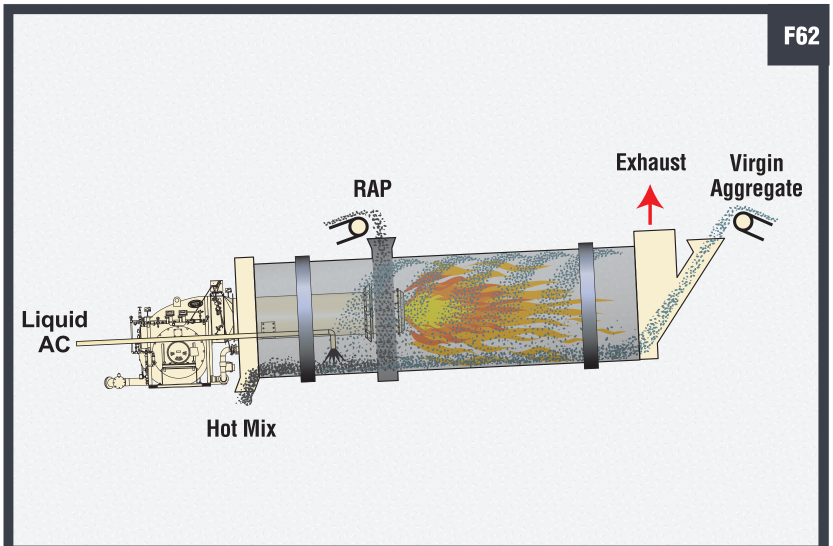
F60



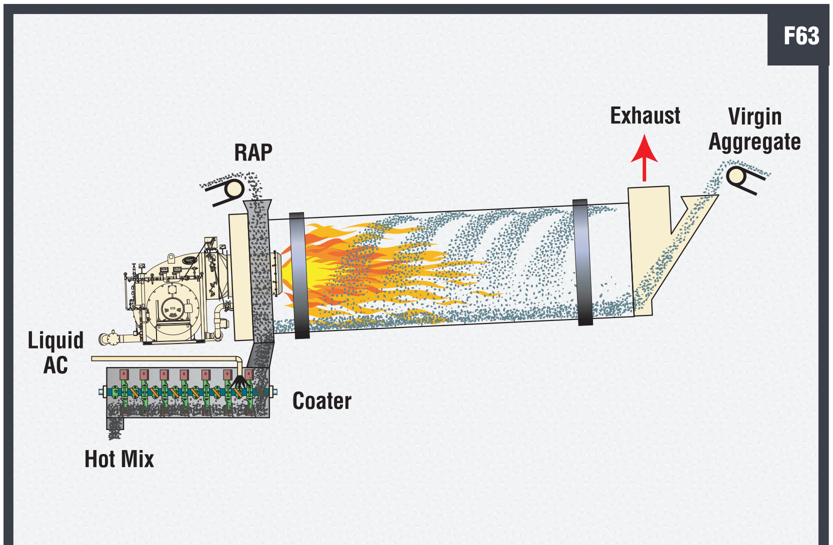
Parallel Flow Drum Mixer



Parallel Flow Drum Mixer With Coater



Counterflow Drum Mixer



Counterflow Drying Drum With Coater

flow drum mixer with a coater (**Fig. 61**), counterflow drum mixer (**Fig. 62**). and a counterflow drying drum with a coater (**Fig. 63**), or a Double RAP™ dryer as shown in **Fig. 64**. The Double RAP dryer has an internal drying drum for superheating virgin aggregate as well as an outer chamber where the hot virgin rock is mixed with RAP prior to entering a separate coater. The Double Barrel® combination dryer/mixer is designed for running high percentages of RAP (**Fig. 65**). It has an internal drying drum for drying the virgin aggregate and an outer chamber for mixing hot aggregate, RAP, and liquid AC.

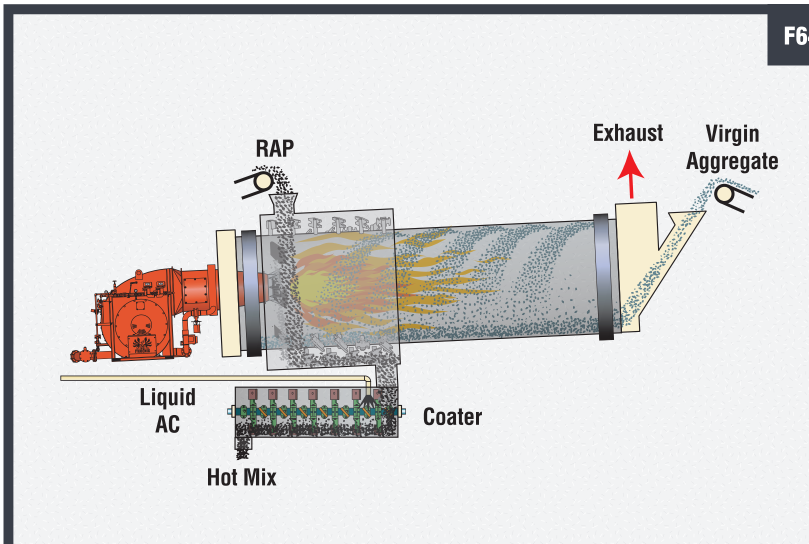
When running RAP through a parallel flow drum or batch plant, it is imperative to keep the recycle as dry as possible to prevent excessive stack emissions. The steam from the drying process will strip the light oil from the virgin asphalt which can oil-soak the baghouse and lead to visible emissions. If the recycle is very wet, scavenge systems on batch plants are usually inadequate to pull the steam surge from the pugmill as the RAP is injected.

Stage Two—10 to 20% RAP

As the percentage of recycle in the mix increases, it is difficult to maintain the gradation and asphalt content in the final mix unless care is taken to prevent segregation in the RAP stockpile. Using telescoping stackers to layer the recycle immediately after it is crushed (**Fig. 66**) will allow a more consistent stockpile that will produce a better quality mix. Care should also be taken to screen the recycle so that no material larger than the maximum size expected in the final mix is allowed to enter the plant.

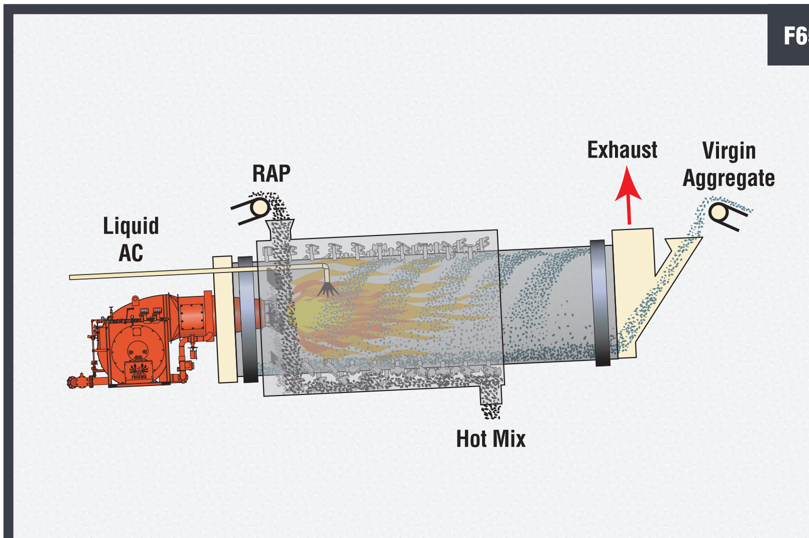
As the percentage of RAP increases in batch plants, operators must consider the steam created as the RAP is heated by the hot virgin aggregate during the mixing process. Since the steam is generated almost instantly, a system that controls and extends the

F64



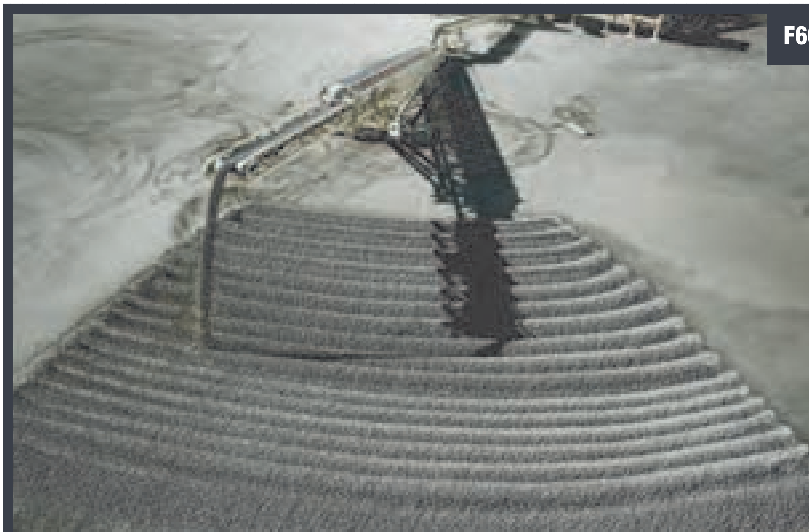
Double RAP™ Dryer With Coater

F65

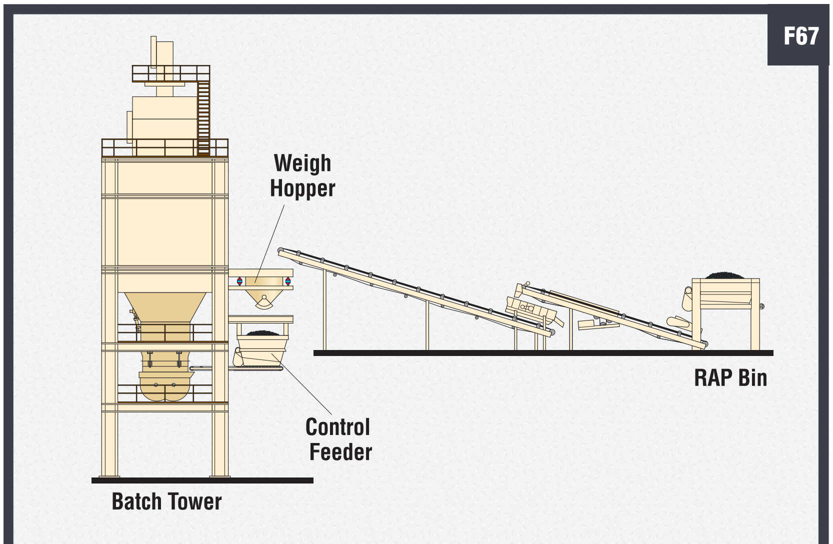


Double Barrel® Combination Dryer/Mixer

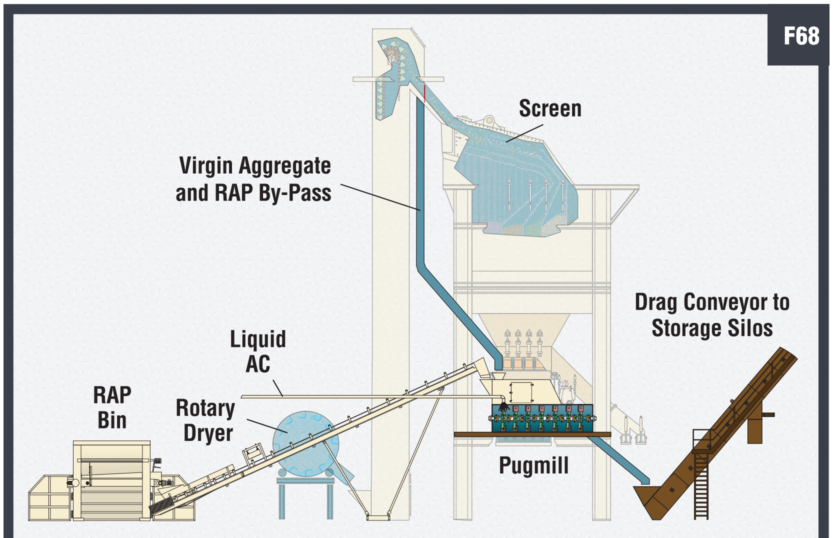
F66



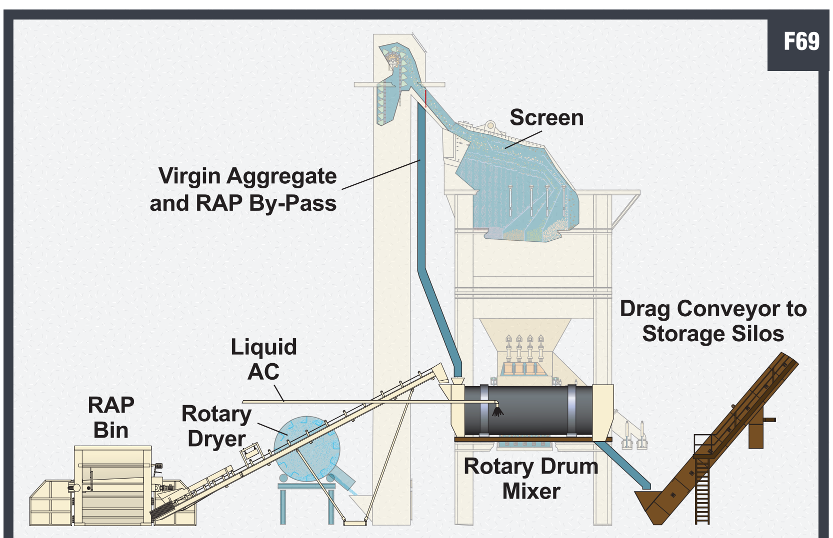
Telescoping Stacker



RAP Delivery System for Batch Plants



Batch Plant with Pugmill Mixer



Batch Plant with Drum Mixer

time of RAP injection into the pugmill should be used (**Fig. 67**). This will give the scavenge system more time to evacuate the steam. As mentioned above, keeping the recycle as dry as possible will reduce the steam and drying cost.

Batch plants are often converted into combination or continuous facilities to allow the use of more RAP. Two such plants are shown in **Fig. 68.** and **Fig. 69**. In these plants, the aggregate is superheated in the dryer and diverted from the bucket elevator directly to a pugmill mixer (**Fig. 68**), or to a mixing drum (**Fig. 69**). The recycle is fed directly into the pugmill or mixing drum where the liquid asphalt is injected and the three components are mixed. The steam from the RAP is continuously pulled from the pugmill or drum mixer to the baghouse.

Batch plants can also be equipped with a Double RAP dryer in which the recycle is heated prior to entering the batch plant (**Fig. 70**). The RAP is then sent directly to a fifth hot bin. This method allows for maximum versatility, since the mix designer can use 0% to 50% RAP in batch mixes.

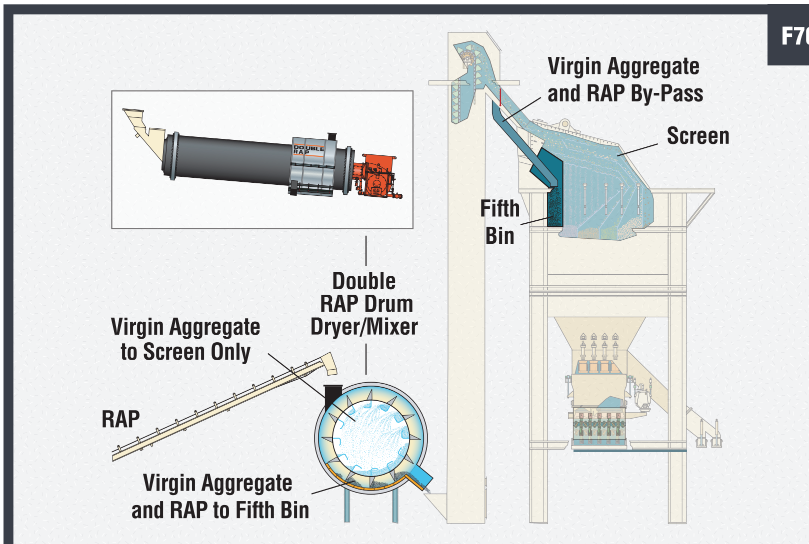
Stage Three—20 to 30% RAP

To control air voids in Superpave mixes, the consistency of RAP becomes more critical when the recycle content exceeds 20%. When increasing the RAP content above 20%, the recycle material should be crushed, screened, and separated into the same sizes as the virgin aggregate that is used in the mix. Both milled RAP and recycle ripped up from the roadway require crushing and screening to control the gradation. Approximately 75% of typical milled RAP will pass through a 1/2-inch screen, reducing the volume of material that must be crushed.

Impact crushing systems are the most suitable for processing milled RAP before it is added to HMA. These crushers break and separate the recycle material, hopefully without fracturing the aggregate. It is best to separate the material at the bonded surface, exposing the recycled aggregate to as little crushing as possible. Ideally, the separation process will only return the recycled aggregate to its original size.

For low RAP capacities, the asphalt plant's recycle feed system should have a return conveyor to send oversized RAP to a crusher (**Fig. 71**). Larger impact crushers as shown in **Fig. 72** should be used for larger

F70



Batch Plant with Double RAP Dryer

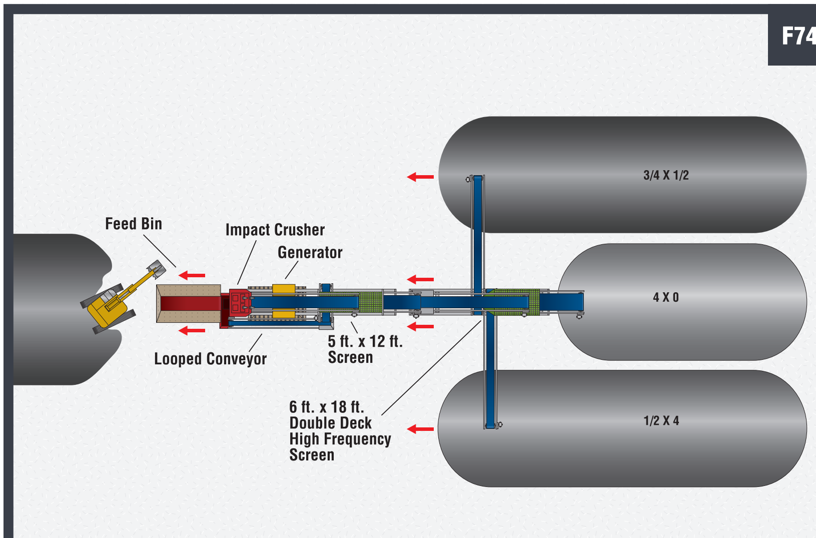
F71

Horizontal Shaft Impactor for Low RAP Capacities

F72

Horizontal Shaft Impactor for High RAP Capacities

Track-Mounted Crusher with Screen



Track Mount RAP Screen Plant

Stationary RAP Screening Plant

sizes and quantities of RAP. **Fig. 73** shows a track-mounted crusher with an onboard screen for crushing and screening recycle.

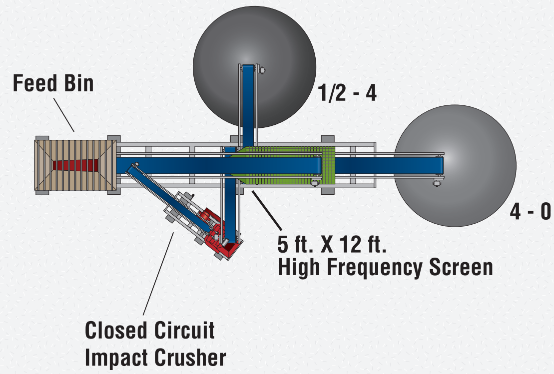
The unit can produce a 1/2-inch by 0 or 3/4-inch by 0 product. By feeding a track mounted screening plant with the crusher as shown in **Fig. 74,** three products can be produced while the crusher and screen is fed by an excavator as it walks through the pile.

The facility shown in **Fig. 75** is a stationary crusher with a feeder and high-frequency screen. The facility produces both a 1/2-inch by 1/4-inch and a 1/4-inch by 0 product to feed the asphalt plant in the background. The facility shown in **Fig. 76** is also producing 1/2-inch by 4 and 4 x 0 products. The gradiation of the products is shown in **Fig. 77.** The standard deviation of these RAP products was less than the same virgin sizes. For processing only milled material, a portable screening plant (**Fig. 78**) can be moved from facility to facility to separate the RAP into three sizes: 1/4-inch minus, 1/2-inch by 1/4-inch, and oversized material to be crushed later. **Fig. 79** shows a similiar unit with a closed circuit crusher producing three products.

Proper management of material gradation is the key to producing high quality, high RAP-content mixes. The sensitivity of the material gradation becomes apparent when observing the fractionated sizes of RAP as mentioned earlier. If the producer has a stockpile of 1/2-inch surface mix with an asphalt content of 6%, after processing it into a 1/2-inch by 1/4-inch material the asphalt content will be between 3 and 3.5%, while the 1/4-inch by 0 RAP will have approximately 7 to 7.5% asphalt. The liquid asphalt content is a direct function of the surface area of the material. The finer the material, the higher its surface area, and consequently it will contain more liquid asphalt. When the material is only processed to 1/2-inch by 0 and becomes segregated, then the asphalt and dust contents in the final mix will vary up and down, depending on the concentrations of either fine or coarse RAP sent to the plant.

Most asphalt facilities in the 1980's and 1990's were similar to the plant

F76



RAP Screening Plant

F77

Gradation and Liquid Asphalt Content (Fine and Coarse) with Standard Deviations

FINE RAP HISTORY

	25.0mm	19.0mm	12.5mm	9.5mm	4.75mm	2.36mm	0.60mm	0.150mm	0.075mm	% AC
Date	1"	3/4"	1/2"	3/8"	#4	#8	#30	#100	#200	
Average	100	100	100	99.4	91.9	76.8	50.0	18.208	10.09	5.76
STD	0.0	0.0	0.0	0.8	2.1	3.1	3.2	1.7	1.0	0.4

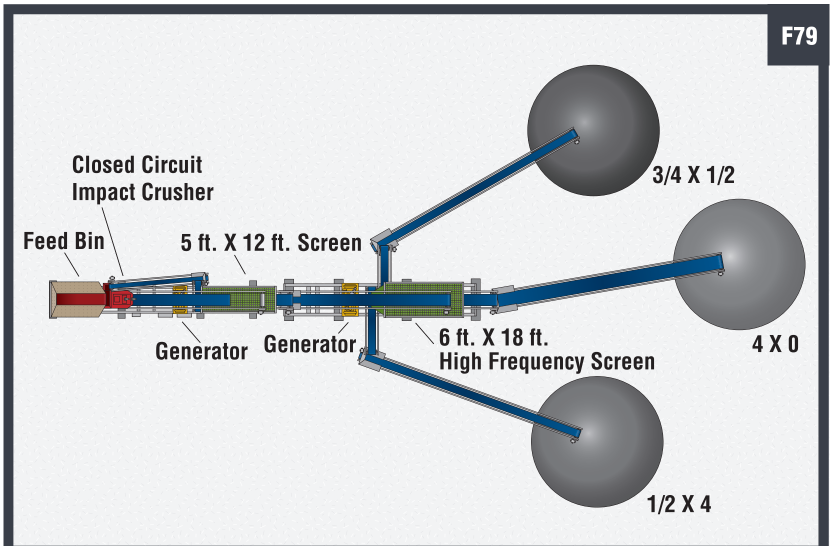
COARSE RAP HISTORY

	25.0mm	19.0mm	12.5mm	9.5mm	4.75mm	2.36mm	0.60mm	0.150mm	0.075mm	% AC
Date	1"	3/4"	1/2"	3/8"	#4	#8	#30	#100	#200	
Average	100	100	92.707	70.2	27.2	19.6	13.8	7.78	5.64	3.20
STD	0.0	0.0	3.4	5.0	2.1	1.8	2.6	1.8	1.4	0.2

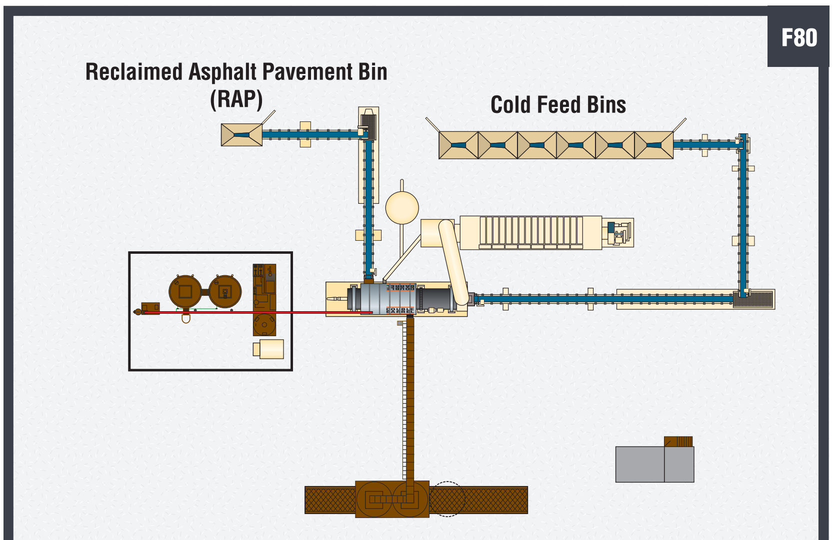
RAP Gradiations

F78

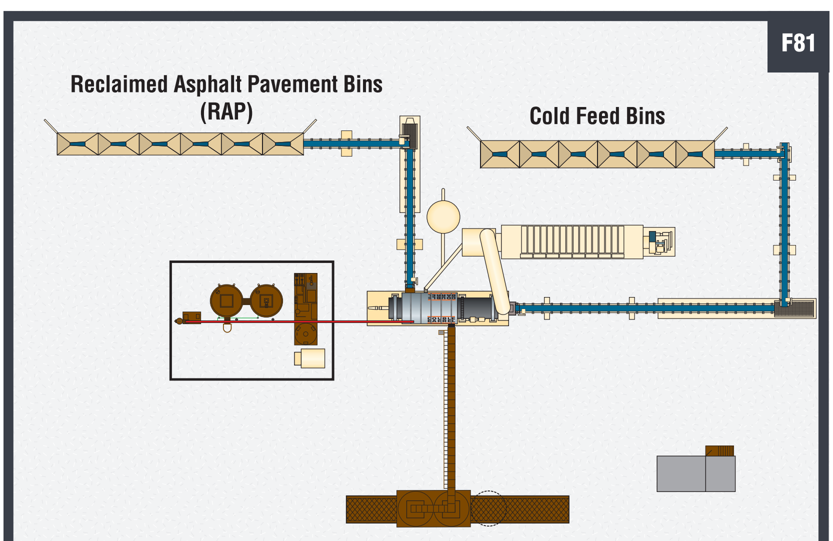
Portable Screening Plant



Portable Impact Screen Plant



1980-1990's HMA Facility with Single RAP Bin



Today's HMA Facility with Multiple RAP Bins

layout shown in **Fig. 80**. These facilities most often had four to five virgin cold feed bins and only one recycle bin. When using RAP at 20% and higher, a plant similar to the one shown in **Fig. 81** should be used. On this plant, the recycle material is separated into exactly the same sizes as the virgin aggregate. By having the same gradation of both the virgin rock (white rock) and RAP (black rock), the mix designer can simply choose the gradation of the desired mix then select either black or white rock. This gives the mix designer substantially more flexibility, and it allows for the use of RAP in virtually all mixes.

Generally, the 1/4-inch by 0 RAP can be used in all mixes, and it has the highest amount of liquid asphalt. This size recycle is therefore the most valuable RAP product. This recycle material is also more versatile than larger sizes because skid numbers are not measured on fine aggregates, even when skid-resistant aggregate is required for high traffic roads. Therefore 1/4-inch by 0 RAP previously made from a non-skid material can be used as a recycle product in a skid-type mix. The separation of the recycle material gives the mix designer considerably more flexibility in the size and percentage of RAP used in different mixes.

Stage Four—30 to 40% RAP

In all counterflow drum plants, the recycle material is heated and melted by transferring energy from superheated virgin rock to the recycle material. **Fig. 82** shows the temperature to which the virgin rock must be heated in a standard counterflow dryer based on the amount of moisture in the RAP and the desired temperature of the final mix. As shown in the table, a producer wanting to produce a 40% RAP mix with recycle that contains 5% moisture must superheat the virgin aggregate to 608˚F in order to produce a 300˚F mix. RAP with lower moisture contents therefore require less heating of the virgin rock. With this in mind, it is important for producers to keep the recycle material as dry as possible, particularly as the percentage of RAP increases in the plant's mixes.

When using more specialized equipment like the Double Barrel dryer/mixer (**Fig. 83**) or a counterflow dryer with a RAP heater such as the Double RAP dryer shown in **Fig. 84**, less superheating is required. This is because a considerable amount of heat is transferred from the drying drum to the RAP mix via the inner drum shell, mixing shanks, and tips. **Fig. 85** shows the temperature that must be reached in a traditional counterflow dryer to superheat aggregate when 50% RAP is used. **Fig. 85** also shows how the Double Barrel dryer/mixer requires approximately 100˚F less heat to run the same amount of recycle. The Double Barrel and Double RAP dryer work on similar principles, making them both particularly advantageous when using highly absorptive aggregates, since this rock tends to break apart if superheated too quickly or to an excessive temperature.

Unlike in the Double Barrel dryer/mixer and Double RAP dryer, the amount of heat loss from a counterflow dryer increases considerably as the amount of superheat increases. Generally, the shell temperature will either equal or exceed the temperature of the aggregate. An infrared photograph of a counterflow dryer running 20% RAP is shown in **Fig. 86**. The scale on the left shows a temperature range from 250˚F to 800˚F. The crosshairs on the photograph show spot temperatures. Note that colors used in this and the following infrared photographs only show temperature differences. A new color scale is included on the left side of each infrared photograph to show its temperature range.

F82

RAP Content (%)	RAP Moisture Content (%)	Superheat Required (˚F)			
		240˚F Mix	260˚F Mix	280˚F Mix	300˚F Mix
10	0	269	291	313	335
	1	274	296	318	340
	2	279	301	323	345
	3	284	306	328	350
	4	289	311	333	355
	5	294	316	338	360
20	0	292	317	342	367
	1	303	328	353	378
	2	314	339	364	389
	3	325	350	375	400
	4	336	361	386	411
	5	347	372	397	422
30	0	324	352	330	408
	1	343	371	599	427
	2	362	390	418	446
	3	381	409	437	465
	4	400	428	456	484
	5	419	447	475	503
40	0	366	397	430	463
	1	424	426	459	492
	2	453	455	488	521
	3	482	484	517	550
	4	511	513	546	579
	5	540	542	575	608
50	0	420	460	500	540
	1	464	504	544	588
	2	508	548	588	628
	3	552	592	632	672
	4	596	636	676	716
	5	640	680	720	760

NOTE: Calculations assume 10˚F loss from dryer to pugmill and 70˚F outside air temperature.

Standard Counterflow Dryer (superheat required)

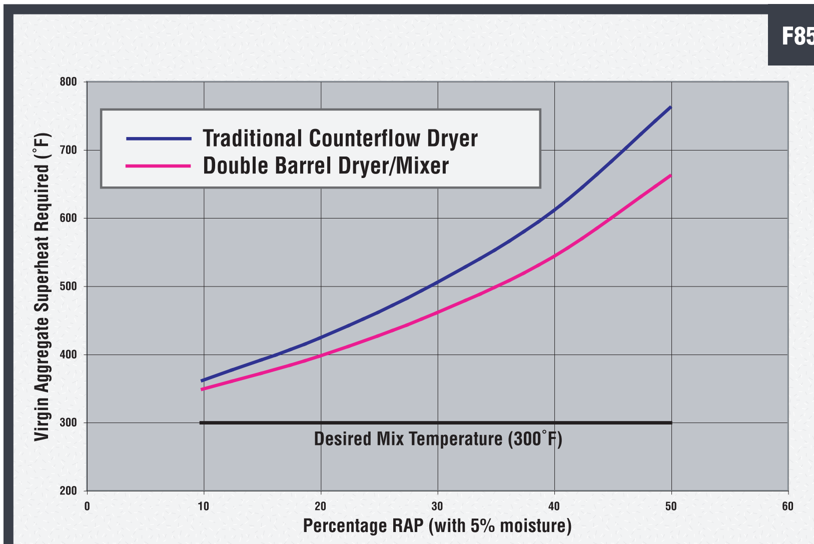
F83

Double Barrel® Dryer/Mixer

F84

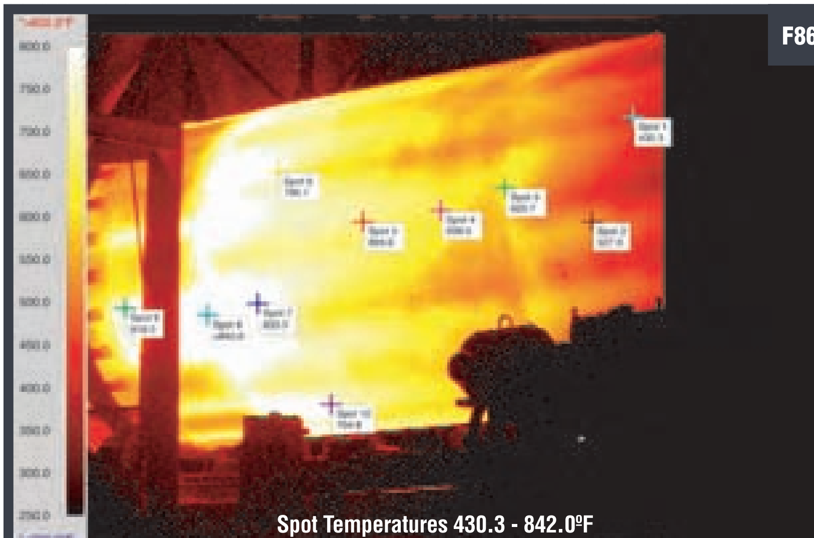
Double RAP® Dryer

F85



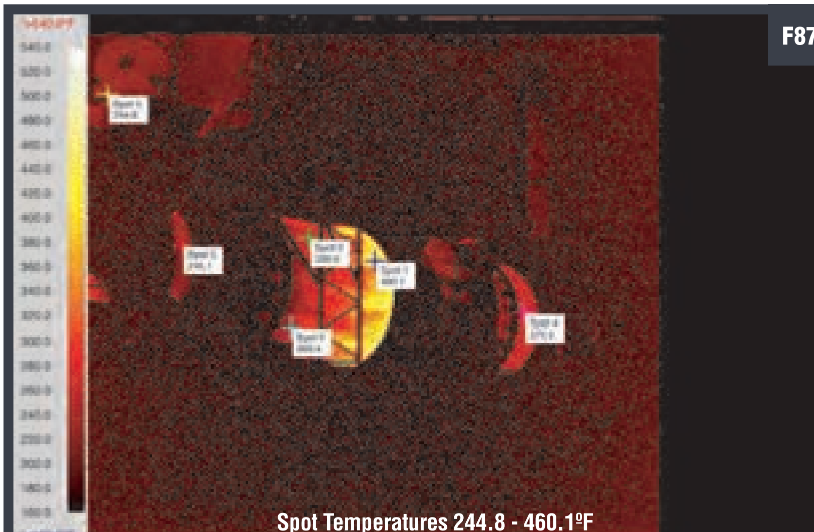
Double Barrel® vs. Counterflow Dryer (superheat required)

F86



Counterflow Dryer Running 20% RAP

F87



Counterflow Mixer Running 20% RAP

A counterflow drum mixer running 20% RAP also experiences significant heat loss (**Fig. 87**). Shell temperatures further increase with 40% RAP; **Fig. 88** shows shell temperatures as high as 540˚F. As RAP content increases, the heat loss and the additional fuel required significantly increase production costs. Also as RAP percentages increase, more time is required to dry and heat the RAP, cool the virgin aggregate, transfer old liquid to the virgin rock, add new AC, add dust, and then mix all ingredients.

At Stages Four and Five recycle, continuous mix plants with the Double Barrel dryer/mixer are most desirable, because all heat from the drying drum shell is transferred directly into the mix. **Fig. 89** shows the Double Barrel's shell temperatures when running 30% RAP—notice that the highest temperature is only 248˚F. The Double Barrel's long mixing chamber allows the RAP to be heated, the moisture evaporated, the virgin aggregate cooled, old liquid transferred to the virgin aggregate, and the temperature equalized prior to adding the new liquid AC and dust. Only short mixing times are possible with traditional equipment, preventing mixes with high contents of RAP from reaching optimal mix temperature. These mixers, in turn, create a poor quality mix when the recycle content exceeds 30%.

Producers must also consider the type of liquid asphalt necessary in high RAP-content mixes. As the percentage of recycle increases over 20%, many states require a softer grade of liquid. A second AC tank can be added to the plant, allowing the facility to store both a standard asphalt and lower grade or a flux material (**Fig. 90**). By using flux oil, which can be blended directly into standard grade liquid asphalt, the hardness of the asphalt can be reduced on-site.

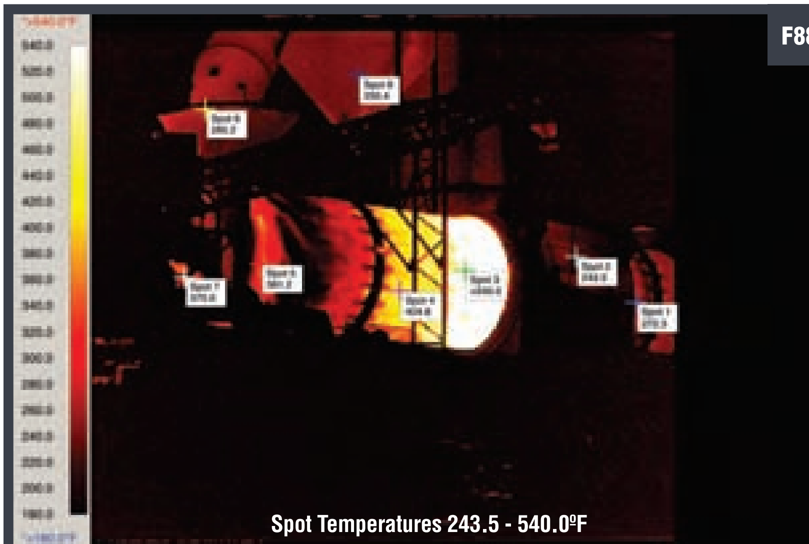
Despite regulations set by state DOT's, it is the author's opinion that adding a soft grade or a flux oil is unnecessary. Asphalt mixes in Europe are commonly produced with a harder grade of liquid than in the United States. These pavements are placed in equal or cooler climates than in America, and the surfaces show no sign of poor mix quality. Furthermore, by using a standard grade of asphalt instead of fluxing the AC, a purer liquid goes into the mix, promoting longer pavement life.

Stage Five—40 to 50% RAP

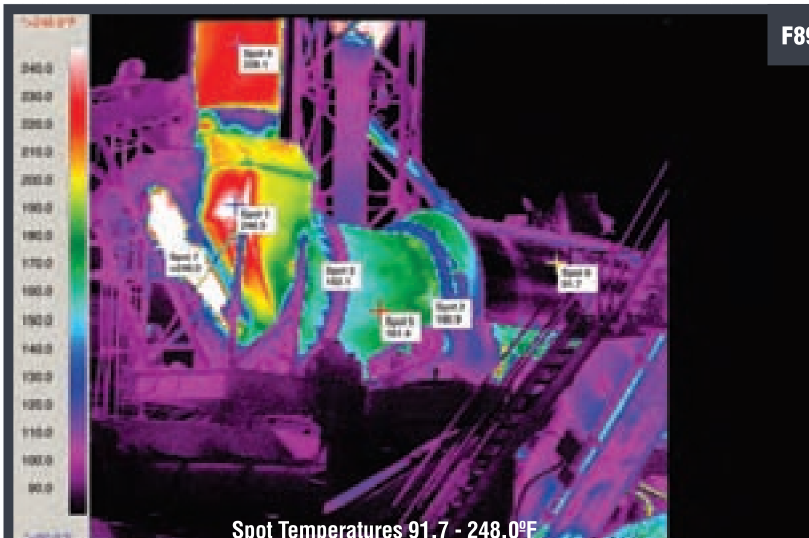
When the RAP content in mixes produced in continuous mix plants exceeds 20%, the recycle must be processed and fed from multiple bins to control the gradation of the RAP. Also, the production equipment must ensure a long mixing time and capture excess heat from the drying drum. The Double Barrel dryer/mixer is ideal for running high RAP-content mixes because of its long mixing chamber and ability to capture heat from the drying chamber. With the Double Barrel, fuel consumption remains virtually unchanged whether the plant is running 50% RAP or all-virgin mixes.

When producing mixes with 40 to 50% recycle then switching to all-virgin mixes, controlling stack temperature is extremely difficult. Newer burners as shown in **Fig. 91** utilize variable frequency drives to control the fuel metering pump and burner blower. A computerized control system (**Fig. 92**) controls both the blower and pump speed through variable drives. This allows the plant operator to control the air and fuel independently throughout the complete range of production. If the drum is equipped with sufficient flighting, these controls can be utilized to lower the stack temperature to approximately 250˚F when producing mixes with 50% recycle. When changing to an all-virgin mix, the excess air to the burner can be increased to raise the stack temperature.

European batch plants can produce mixes with up to 50% RAP using a parallel flow drum as a recycle heater. The drying drum is mounted on a platform at the top of the batch tower, and RAP is fed to the dryer by an elevator or drag chain. The drum



Counterflow Mixer Running 40% RAP

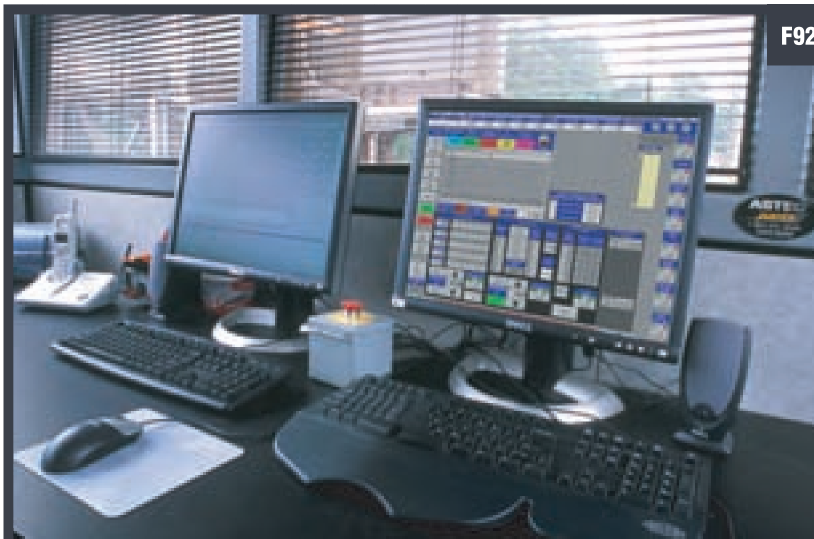


Double Barrel® Dryer/Mixer Running 30% RAP

HMA Plant with Two Liquid AC Tanks

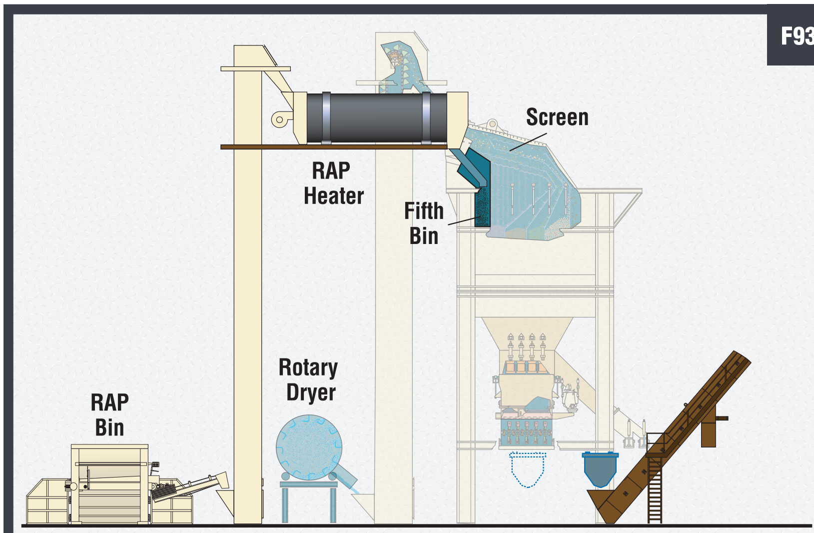
F91

Phoenix® Talon Burner with VFD's



F92

Burner Control System



F93

European RAP Heating System for Batch Plants

heats the recycle material to approximately 240˚F, keeping the RAP below its smoke point temperature. The heated recycle is sent directly to the tower's fifth bin and then to the pugmill (**Fig. 93**). Mixing time must also be increased significantly when running 50% RAP in this type of batch plant. These batch plants are generally very low production and extremely expensive. A counterflow dryer with an outer aggregate blending chamber, like the Double RAP dryer, is the best option for batch plants producing high RAP-content mixes.

When running 40% to 50% recycle on any plant, special care must be taken to maintain a continuous flow of recycle material to the mixing facility. Because the virgin aggregate is superheated, stopping the flow of RAP will cause the virgin AC to come into direct contact with the superheated rock and subsequently catch fire. Producers must therefore use a control system that is capable of monitoring the flow of RAP and the temperature in the mixing chamber. When using a Double Barrel dryer/mixer and an appropriate computerized control system, an alarm will sound if the temperature in the mixing chamber suddenly rises or if the RAP flow stops.

One final note to consider when producing mixes with high RAP content is the added wear and tear on the equipment due to the high temperatures needed during production. While mixes with as much as 50% RAP are consistently produced by many plants today, these facilities must be more carefully monitored than those running all-virgin mixes. Plant operators must carefully monitor the drum shell, T-flights, and all other components exposed to the increased temperatures. The resulting decrease in drum life must also be factored into future maintenance costs if mixes with 50% RAP are consistent.

V. FINAL THOUGHTS AND SUGGESTIONS

Recycled asphalt is a particularly valuable material to the HMA industry, and its value will continue to increase as the cost of virgin aggregate and asphalt rise. For that reason, producers who can supply mixes with RAP will be best prepared to compete in future markets. As discussed, the production of mixes with recycle requires understanding of a few basic rules in order to ensure a high quality mix and minimum fuel usage. Regardless of the amount of recycle used in a mix, the following suggestions should be followed:

1. Process the RAP to the same sizes as the virgin material to ensure consistent gradation and uniform asphalt content.

2. Keep the recycle material as dry as possible to minimize the amount of steam that is released when the RAP comes into contact with superheated virgin aggregate. Ideally, the recycle material should be either crushed and immediately placed in an enclosed building for storage, or it should be crushed and screened each day as the RAP is needed.

3. Keep RAP separate from start-up waste. All mixes are produced with a film thickness of nine to ten microns. If the recycle material is screened to the same size as the virgin aggregate, its asphalt content will be uniform. In contrast, start-up waste generally contains too little or too much asphalt. It can be returned to the plant, but it should be added to the new mix at very small percentages and through a separate bin.

VI. CONCLUSION

In conclusion, producers must understand that RAP is not a waste product. Like materials from a quarry or oil well, roads are another source of aggregate and liquid asphalt. Furthermore, the ingredients in recycle are the same age as virgin aggregate and liquid asphalt. RAP is worth the virgin material it replaces ton for ton.

If recycle is processed and treated the same as virgin materials, mixes with up to 50% RAP can be produced while maintaining a level of quality that is equal or superior to that of all-virgin HMA. When properly processed and mixed, RAP can also significantly reduce the cost of asphalt production. RAP has the added advantage of conserving natural resources and providing more miles of pavement from available revenues. In the US, state DOT's should recognize the value of the material removed from their roadways and develop trade-in programs for old pavement to reduce the cost of new pavement. As virgin resources become more limited and prices rise, contractors with the technology to efficiently obtain, process, and utilize RAP in HMA mixes will have a significant competitive advantage.