



**PDHonline Course C184 (3 PDH)**

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## **Reclaimed Asphalt Pavement (RAP)**

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## INTRODUCTION

Reclaimed asphalt pavement (RAP) can be used as an aggregate in the hot recycling of asphalt paving mixtures in one of two ways. The most common method (conventional recycled hot mix) involves a process in which RAP is combined with virgin aggregate and new asphalt cement in a central mixing plant to produce new hot mix paving mixtures.<sup>(1)</sup> A second method (hot in-place recycling) involves a process in which asphalt pavement surface distress is corrected by softening the existing surface with heat, mechanically removing the pavement surface, mixing it with a recycling or rejuvenating agent, possibly adding virgin asphalt and/or aggregate, and replacing it on the pavement without removing the recycled material from the pavement site.<sup>(2)</sup>

## PERFORMANCE RECORD

Although some form of pavement recycling had been practiced as early as 1915,<sup>(3)</sup> the first sustained efforts to recover and reuse old asphalt paving materials were conducted during 1974 in Nevada and Texas.<sup>(4)</sup> Bolstered by the sponsorship of the Federal Highway Administration (FHWA), more than 40 states performed and documented RAP demonstration projects between 1976 and 1982.

RAP is now routinely accepted in asphalt paving mixtures as an aggregate substitute and as a portion of the binder in nearly all 50 states. Substitution rates of 10 to 50 percent or more, depending on state specifications, are normally introduced in pavements, and recently developed technology has even made it possible to recycle 90 to 100 percent RAP in hot mix.

### Recycled Hot Mix

The use of processed RAP to produce conventional recycled hot mix (RHM) is the most common type of asphalt recycling and is now considered standard asphalt paving practice. There are abundant technical data available indicating that properly specified and produced recycled hot mix asphalt is equivalent in quality and structural performance to conventional hot mix asphalt in terms of rutting, raveling, weathering, and fatigue cracking. Recycled hot mix asphalt mixtures also generally age more slowly and are more resistant to the action of water than conventional hot mix asphalt. (See references 5,6,7,8,9,10, and 11.)

The maximum limit for RAP content in RHM produced in conventional hot mix asphalt batch plants is widely considered to be 50 percent, limited by both the heat capacity of the plants and gaseous hydrocarbon emissions. As much as 60 to 70 percent RAP may be processed in drum mix plants. Special plants based on microwave technology have been developed to limit gaseous emissions from hot mix asphalt production using very high RAP contents (up to 100 percent RAP), but the cost of heating is much higher than that of conventional systems. This process was developed in California and has only seen limited use.<sup>(12)</sup>

Table 13-3 provides a 1996 list of State Department of Transportation (DOT) specification requirements for the use of RAP in hot mix asphalt paving mixtures. Separate requirements are given for mixes produced in batch plants or drum-mix plants. Maximum allowable RAP percentages are shown in Table 13-3 for wearing surface, binder, and base courses.<sup>(13)</sup>

While all state highway agencies permit the use of RAP in base and binder courses, 10 agencies do not permit the use of RAP in surface courses. These include Alaska, Florida, Hawaii, Louisiana, Maine, Maryland, New York, Oklahoma, Rhode Island, and Tennessee. Louisiana and Maine allow up to 20 percent RAP in shoulder mixes only. Massachusetts does not permit the use of RAP in open-graded friction course mixes.<sup>(13)</sup> Minnesota permits RAP to be used in surface mixes only on low-volume roads.<sup>(5)</sup> Oklahoma allows up to 25 percent RAP for low-volume roads (fewer than 1,000 vehicles per day) only. Oregon does not permit RAP use in surface mixes on interstate highways.<sup>(13)</sup>

States that approve the use of RAP in surface courses generally permit from 10 to 30 percent RAP. Some states permit even higher percentages from approved RAP sources. Allowable binder and base course aggregate substitution rates range from 10 to as high as 70 percent in one state (Arkansas). At least 22 states do not permit the blending or commingling of RAP from different projects into combined stockpiles.<sup>(13)</sup>

### Hot In-Place Recycling

The use of hot in-place recycling (HIPR) has developed rapidly over the past decade, although it is in use only on a limited basis. Simple heater-scarification units, heat reforming systems, and special techniques have been developed for heating, scarifying, rejuvenation, and remixing of up to 50 mm (2 in) in depth of aged old asphalt pavement to new hot mix quality overlay in one pass.

The Asphalt Recycling and Reclaiming Association (ARRA) recognizes three basic HIPR processes: (1) heater-scarification (multiple pass); (2) repaving (single pass); and (3) remixing.

The first two processes involve removal, rejuvenation, and replacement of the top 25 mm (1 in) of the existing pavement. The remixing process involves incorporating virgin hot mix with the recycled paving material in a pugmill and placement to a depth of 50 mm (2 in).

**Table 13-3. State DOT specification requirements for the use of reclaimed asphalt pavement (RAP) in hot mix asphalt paving mixtures.<sup>(13)</sup>**

State	Max. RAP % – Batch Plants			Max. RAP % – Drum Plants			Top Size for RAP
	Base	Binder	Surface	Base	Binder	Surface	
Alabama	40	40	15	50	50	15	2 in.
Alaska	–	–	–	–	–	–	–
Arizona	30	30	30	30	30	30	1.5 in.
Arkansas	70	70	70	70	70	70	3 in.
California	50	50	50	50	50	50	2 in.
Colorado	15	15	15	15	15	15	1.5
Connecticut	40	40	40	40	40	40	2 in.
Delaware	35	35	25	50	50	30	2 in.
Florida	60	50	None	60	50	None	Specs
Georgia	25	25	25	40	40	40	2 in.
Hawaii	30	None	None	40	None	None	1.5 in.
Idaho	Open	Open	Open	Open	Open	Open	2 in.
Illinois	50	25	15	50	25	15	Specs
Indiana	50	50	20	50	50	20	2 in.
Iowa	Open	Open	Open	Open	Open	Open	1.5 in.
Kansas	50	50	50	50	50	50	2 in.
Kentucky	30	30	30	30	30	30	Specs
Louisiana	30	30	None	30	30	None	2 in.
Maine	40	40	None	40	40	None	1 in.
Maryland	Open	Open	Limit	Open	Open	Limit	Specs
Massachusetts	20	20	10	40	40	10	.75 in.
Michigan	50	50	50	50	50	50	Specs
Minnesota	59	50	30	50	50	30	3 in.
Mississippi	30	30	15	30	30	15	2 in.
Missouri	50	50	50	50	50	50	1.5 in.
Montana	50	50	10	50	50	10	2 in.
Nebraska	Not Used	Not Used	Not Used	Open	Open	Open	2 in.
Nevada	50	50	15	50	50	15	1.5 in.
New Hampshire	35	35	15	50	50	15	Specs
New Jersey	25	25	10	25	25	10	2 in.
New Mexico	Open	Open	Open	Open	Open	Open	1.5 in.
New York	50	50	None	70	70	None	2 in.
North Carolina	60	60	60	60	60	60	2 in.
North Dakota	50	50	50	50	50	50	1 in.
Ohio	50	35	20	50	35	20	2 in.
Oklahoma	25	25	None	25	25	None	2 in.
Oregon	30	20	20	30	20	20	1 in.
Pennsylvania	Open	Open	Open	Open	Open	Open	2 in.
Rhode Island	30	30	None	30	30	None	1.25 in.
South Carolina	30	25	20	30	25	20	2 in.
South Dakota	Not Used	Not Used	Not Used	50	50	50	1.5 in.
Tennessee	15	Open	None	Open	Open	None	Open
Texas	15	Open	Open	Open	Open	Open	2 in.
Utah	Not Used	Not Used	Not Used	25	25	25	2 in.
Vermont	Specs.	Specs.	Specs	Specs	Specs	Specs	Specs
Virginia	25	25	25	25	25	25	2 in. Open
Washington	Open	Open	Open	Open	Open	Open	Open
West Virginia	Open	Open	Open	Open	Open	Open	Open
Wisconsin	Open	35	20	Open	35	20	Open
Wyoming	50	50	50	50	50	50	2 in.

The major advantage of HIPR is the cost savings that it can potentially achieve over conventional recycled hot mix, eliminating the costs associated with transporting, processing and stockpiling RAP. Since only the top 50 mm (2 in) of pavement can normally be reconditioned using this process, HIPR applications are limited to roadways that do not have any structural deficiencies and do not require additional materials. The major disadvantage of HIPR is the inability to make significant changes to the mix. Pavements that exhibit structural base failure, irregular patching or the need for major drainage or grade improvements are not suitable candidates for HIPR.<sup>(2)</sup>

Not all states have experience in HIPR applications, although HIPR technology is a fairly well accepted practice. There are 32 states that report having some experience with HIPR, although 22 of these states consider their use of HIPR to be experimental. The 10 states that have the most experience with HIPR are Arkansas, Colorado, Florida, Kansas, Maryland, New York, Ohio, Texas, Utah, and Virginia. None of these states has had more than five HIPR projects per year. A survey of these states found that, in general, all have reported good or fair performance.<sup>(2)</sup>

The survey of HIPR experience at the state DOT level further indicated that the use of the three different HIPR processes has been fairly evenly divided, with 13 states having had some experience with heater-scarification, and 16 states each having some experience with either the repaving or the remixing process. Of the 10 states with the most HIPR experience, 5 have used heater-scarification, 4 have used the repaving process, and 6 have used the remixing process.<sup>(2)</sup>

## **MATERIAL PROCESSING REQUIREMENTS**

### **Recycled Hot Mix**

Reclaimed asphalt pavement must be processed into a granular material prior to use in hot mix applications. A typical RAP processing plant consists of a crusher, screening units, conveyors, and stacker. It is desirable to produce either a coarse or a fine fraction of processed RAP to permit better control over input to the hot mix plant and better control of the mix design. The processed RAP used in recycled hot mix asphalt should be as coarse as possible and the fines (minus 0.075 mm (No. 200 sieve)) minimized. Gentle RAP crushing (controlled crusher speed and clearance adjustment on exit gate) is recommended to minimize the fracture of coarse aggregate and excess fines generation.

### **Hot In-Place Recycling**

In the HIPR process, the surface of the pavement must be softened with heat prior to mechanical scarification. The HIPR process has evolved into a self-contained, continuous train operation that includes heating, scarifying, rejuvenator addition, mixing, and replacement.

## **ENGINEERING PROPERTIES**

Some of the engineering properties of RAP that are of particular interest when RAP is incorporated into new asphalt pavements include its gradation, asphalt content, and the penetration and viscosity of the asphalt binder.

*Gradation:* The aggregate gradation of processed RAP is somewhat finer than virgin aggregate. This is due to mechanical degradation during asphalt pavement removal and processing. RAP aggregates can satisfy the requirements of ASTM D692 "Coarse Aggregates for Bituminous Pavement Mixtures" and ASTM D1073 "Fine Aggregate for Bituminous Pavement Mixtures."<sup>(14,15)</sup>

*Asphalt Content and Properties:* The asphalt content of most old pavements will comprise approximately 3 to 7 percent by weight and 10 to 20 percent by volume of the pavement. Due to oxidation aging, the asphalt cement has hardened and consequently is more viscous and has lower penetration values than the virgin asphalt cement. Depending on the amount of time the original pavement had been in service, recovered RAP binder may have penetration values from 10 to 80 and absolute viscosity values at 60°C (140°F) in a range from as low as 2,000 poises to as high 50,000 poises or greater.<sup>(16)</sup>

## **DESIGN CONSIDERATIONS**

### **Recycled Hot Mix**

#### *Mix Design*

The use of processed RAP in hot mix asphalt pavements is now standard practice in most jurisdictions and is referenced in ASTM D3515.<sup>(17)</sup> The primary steps in the design of mixes include the determination of material properties of RAP and new materials, the selection of an appropriate blend of RAP and virgin aggregate to meet gradation, the selection of an appropriate asphalt cement blend to satisfy specified viscosity and/or penetration requirements, the need to add a recycling or rejuvenating agent to soften the existing binder, and the need to comply with stability, flow, and air voids requirements.

Either the Marshall<sup>(18)</sup> or the Hveem<sup>(19)</sup> mix design procedures are used by most state agencies for determining the asphalt cement and acceptable RAP content of recycled paving mixes.<sup>(1)</sup>

Recycling and rejuvenating agents can be divided into three main types: "super-soft" asphalt cements, naphthenic (aromatic) oils, and paraffinic oils. These products consist of organic compounds derived from petroleum extracts during petroleum hydrocarbon processing. ASTM D4552<sup>(20)</sup> provides a classification of recycling or rejuvenating agents.

Procedures for selecting the quality of asphalt cement or recycling agent are outlined in ASTM D4887.<sup>(21)</sup> This specification includes a viscosity blending chart, which enables the designer to determine the percentage of recycling or rejuvenating agent (or soft asphalt cement) to add to the total binder in order to achieve a desired value of absolute viscosity for the recycled asphalt cement. The Asphalt Institute's manual on asphalt hot mix recycling also provides trial mix design examples that indicate how to use a viscosity blending chart to design a recycled hot mix.

The Asphalt Institute suggests that when 20 percent or less RAP is used in a mix, no change in asphalt grade is required. However, for mixes with greater than 20 percent RAP, a drop in one grade (softer asphalt cement) is recommended to compensate for the greater viscosity of the oxidized binder.<sup>(1)</sup> Many states use the same grade of asphalt cement regardless of the RAP content.

The Asphalt Institute's manual on mix design methods for asphalt concrete<sup>(22)</sup> provides a method to determine necessary mix design characteristics (such as stability, flow, and air voids content) for either the Marshall or the Hveem mix design methods. The final mix design proportions for the recycled hot mix paving mixture will be determined by completing mix design testing using standard procedures to satisfy applicable mix design criteria.

Additional virgin aggregates may be required to satisfy gradation requirements to improve stability and to limit the RAP content in recycled hot mixes. In the production of hot mix, superheated virgin aggregate is needed to provide indirect heat transfer to the RAP while maintaining the proper mix temperature without the generation of "blue smoke."

#### *Structural Design*

Conventional AASHTO pavement structural design methods are appropriate for asphalt pavements incorporating reclaimed asphalt pavement in the mix.

### **Hot In-Place Recycling**

#### *Mix Design*

Mix design procedures for HIPR are not as well established as those for conventional recycled hot mix. Many states as a minimum require that cores be taken of the candidate pavement to determine in-place pavement properties, including binder content, viscosity, and aggregate grading.<sup>(2)</sup>

The material properties of the existing asphalt pavement (to at least the depth of scarification) should be determined prior to construction in order to permit any necessary adjustments to aggregate gradation to develop the required voids in mineral aggregate (VMA) and selection of the appropriate viscosity binder. This will require coring of the pavement to be recycled and laboratory testing of the recovered paving samples.

Unlike conventional recycled hot mix where the RAP is combined with a significant amount of new aggregate material (making up typically between 60 to 80 percent of the RHM), HIPR may involve up to 100 percent recycling of the existing pavement. Consequently, the extent to which the existing pavement can be improved or modified is limited by the condition and characteristics of the old mix.

The amount of rejuvenating agent that can be added through HIPR is limited by the air voids content of the existing asphalt. When the air voids content of the old asphalt mix is too low to accommodate sufficient recycling agent for proper rejuvenation or softening of the old asphalt binder without mix flushing, it may be necessary to add additional fine aggregate or to beneficiate with virgin hot mix to open up the mix or increase the air voids. The selection of the appropriate addition (either fine aggregate or virgin hot mix), and the amount to be added, are determined by Marshall or Hveem mix design methods.

The type of recycling or rejuvenating agent and the percentage to be added to the binder can be estimated using procedures outlined in ASTM methods D4552<sup>(20)</sup> and D4887.<sup>(21)</sup> The recycling or rejuvenating agent, if used, should be compatible with the recycled and new asphalt binder.

#### *Structural Design*

HIPR is generally considered a rehabilitation technique for addressing superficial pavement distress to a maximum depth of about 50 mm (2 in). The recycled layer is considered to be structurally equivalent to new hot mix asphalt.

## **CONSTRUCTION PROCEDURES**

### **Recycled Hot Mix**

#### *Material Handling and Storage*

RAP is produced by milling, ripping, breaking, crushing, or pulverizing types of equipment. To ensure that the final RAP product

will perform as intended, inspection of incoming RAP with rejection of contaminated loads (excess granular material, surface treatment, joint sealant, etc.) should be undertaken. Some jurisdictions also require that RAP from a particular project not be blended or commingled with RAP from other projects.

Once processed, RAP can be handled and stored as a conventional aggregate material. However, because of the variability of RAP in comparison with virgin aggregates, many agencies do not permit the blending of RAP from different projects into combined stockpiles. The Asphalt Institute recommends that the height of RAP stockpiles be limited to a maximum of 3 meters (10 ft) to help prevent agglomeration or sticking together of the RAP particles.<sup>(1)</sup> Stockpiling time should also be minimized to keep the moisture content of RAP stockpiles from becoming excessive.

Experience has proven that conical stockpiles are preferred to horizontal stockpiles and will not cause RAP to re-agglomerate in large piles. RAP has the tendency to form a crust (due to a solar/thermal effect from the sun) over the first 200 to 250 mm (8 to 12 in) of pile depth for both conical and horizontal stockpiles. This crust tends to help shed water, but is easily broken by a front-end loader, and may help keep the rest of the pile from agglomerating. RAP has a tendency to hold water and not to drain over time like an aggregate stockpile. Therefore, low, horizontal, flat stockpiles are subject to greater moisture accumulation than tall, conical stockpiles. It is not unusual to find RAP moisture content in the 7 to 8 percent range during the rainy season at facilities using low, horizontal stockpiling techniques.<sup>(23)</sup>

RAP stockpiles are typically left uncovered because covering with tarps can cause condensation under the tarp and add moisture to the RAP stockpile. For this reason, RAP stockpiles are either left uncovered or RAP is stored in an open-sided building, but under a roof.<sup>(23)</sup>

When large quantities of RAP from different sources are available, it is advisable to keep stockpiles separated and identified by source. Consistent RAP from a "composite" or "blended" pile can be produced using a crushing and screening operation and reprocessing stockpiles that come to the yard from different sources. Material handling machinery, such as front-end loaders and bulldozers, should be kept from driving directly on the stockpile. Agglomerating RAP particles can make it very difficult for the loader to handle the RAP.

#### *Mixing, Placing and Compacting*

When RAP is added to hot mix asphalt, measures must be taken to avoid exposing the RAP to temperatures in excess of 427°C (800°F). Exposure of the RAP to temperatures above this limit can result in excessive hydrocarbon emissions (blue smoke). To reduce this problem, hot mix asphalt plants have been modified to permit the recycling of RAP.<sup>(24)</sup>

In a batch plant operation, the RAP is usually added to superheated new aggregate at the pugmill. In drum-mix plants, RAP is usually introduced with new aggregate into the drum using a dual feed system. The new aggregate is typically introduced at the hot end of the drum (normally the front end of the drum), while the RAP is introduced at the middle or rear of the drum to prevent overheating damage to the RAP.<sup>(25)</sup>

In a batch plant, typical RAP substitution rates are limited by the heat capacity of the plant and the ability to superheat the aggregate to temperatures that will produce a suitable mix temperature. This normally limits batch plant blends to between 10 and 30 percent RAP. In a drum mix plant, from 30 to 70 percent RAP can be added, with a practical limit of 50 percent, due to hydrocarbon emission limitations that may be exceeded if excess RAP is introduced.

#### *Quality Control*

To produce consistently high-quality recycled hot mix asphalt, the need for systematic quality control of the RAP is essential. The process should be monitored for processed RAP moisture content, gradation, and asphalt cement content.<sup>(26)</sup> Controlled plant operations have been developed to produce a consistent (homogeneous) RAP. Extraction tests to monitor the RAP gradation and asphalt cement content, and penetration and viscosity tests on the recovered asphalt cement, should be performed regularly to monitor the RAP characteristics for comparison with the job mix formula and enable appropriate adjustments to the mix.

The same field testing procedures used for conventional hot mix asphalt mixes should be used for mixes containing reclaimed asphalt pavement. Mixes should be sampled in accordance with AASHTO T168,<sup>(27)</sup> and tested for specific gravity in accordance with ASTM D2726<sup>(28)</sup> and in-place density in accordance with ASTM D2950.<sup>(29)</sup>

### **Hot In-Place Recycling**

#### *Mixing, Placing and Compacting*

There are three basic HIPR construction processes in use: heater scarification, repaving, and remixing. All involve a specialized plant in a continuous train operation.

Heater scarification involves a plant that heats the pavement surface (typically using propane radiant heaters), scarifies the pavement surface using a bank of nonrotating teeth, adds a liquid rejuvenating additive, then mixes and levels the recycled mix using a standard auger system. The recycled asphalt pavement is then compacted using conventional compaction equipment. The process is limited in its ability to repair severely rutted pavements, which are often overlaid with conventional hot mix

asphalt.

Repaving is a more sophisticated process that includes removing (by heating and scarification and/or grinding) the top 25 to 50 mm (1 to 2 in) of the old asphalt pavement, adding and mixing in a rejuvenating agent to improve asphalt viscosity, placing the recycled material as a leveling course using a primary screed, and simultaneously placing a thin (usually less than 25 mm (1 in) but up to 50 mm (2 in) in some systems) hot mix asphalt overlay. Conventional equipment and procedures are used immediately behind the train to compact both layers of material to ensure a monolithic bond between the new and recycled layer.<sup>(30)</sup>

The remixing process is used when additional aggregates are required to improve the strength or stability of the recycled asphalt concrete. Scarified or milled RAP is blended with rejuvenator and new virgin aggregate or new hot mix asphalt, then placed by a compacting screed. Conventional equipment and procedures are used to place and compact the remixed material.

#### *Quality Control*

The initial step in the quality control of hot in-place recycled mixes is in the selection of the pavement to be recycled. Not all pavements are good candidates for this type of recycling. Cores of the pavement being considered for HIPR must be taken during the early planning for the project. The cores should first be visually examined for pavement problems such as delaminations, stripping, or stripping potential, or water in the voids or delaminations. Pavements with delaminations, especially saturated delaminations, in the top 5 cm (2 in) should not be considered for HIPR projects. Also, pavements that have been rutted, heavily patched, or chip-sealed are not good candidates for HIPR projects.

Next, as noted in the Mix Design section, field core specimens should be analyzed in the laboratory to determine (based on the asphalt content, viscosity, and penetration of the recovered binder) the required amount of rejuvenating agent to be added to the mix in order to attain the desired viscosity of the recycled mix. If too much rejuvenating agent (1.0 percent or more by weight of mix) must be added in order to attain this viscosity, the mix should probably not be recycled in place. As a guideline, pavements being considered for HIPR should not be too severely aged. It is recommended that such pavements have an absolute viscosity lower than 200,000 poises (and preferably below 100,000 poises) in order to be considered for HIPR projects.<sup>(31)</sup>

Field core specimens should also be evaluated for air voids content during the pavement selection process. An existing pavement being considered for HIPR should have an air voids content in excess of 6 percent, in order to accommodate the addition of a rejuvenating agent without the loss of stability in the recycled mix. If material properties are not completely satisfactory for 100 percent recycling, the addition of 20 to 30 percent by weight of virgin hot mix during recycling should be considered.<sup>(31)</sup>

Field quality control measures during HIPR operations include monitoring the depth of scarification, the temperature of the recycled mix, the visual appearance and homogeneity of the scarified or milled RAP, the compaction procedure, and the visual appearance of the recycled pavement surface after compaction. Loose samples of the recycled mix should be obtained and extraction tests performed to monitor RAP gradation, asphalt cement and air voids contents, and penetration and viscosity of the recovered asphalt binder for comparison with the job mix formula.<sup>(32)</sup> The recycled mix should be monitored for in-place density in accordance with ASTM D2950.<sup>(29)</sup>

#### **UNRESOLVED ISSUES**

While the asphalt pavement recycling technologies are well established, there is still considerable need for additional performance information, particularly with regard to creep (rutting resistance), fatigue endurance and durability, and the use of reclaimed asphalt pavement in premium surface course mixes. There is also a need for more correlation of field and laboratory measurements to refine guidelines for laboratory prediction of field performance (for instance, laboratory curing procedures that best simulate field conditions).

Some additional issues that require resolution include:

- further information on the variability of RAP, especially from blended stockpiles;
- validation of SUPERPAVE mix design procedures with mixtures containing RAP;
- an environmental code of practice regarding gaseous emissions from hot mix plant recycling and HIPR;
- the suitability of HIPR for surface-treated and rubberized materials (environmental considerations); and
- evaluation methodologies for structural characterization of HIPR asphalt concrete and CIPR asphalt concrete.

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