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100% hot mix asphalt recycling: challenges and benefits

Martins Zaumanis a*, Rajib B. Mallick b, Robert Frank c

aWorcester Polytechnic Institute (WPI), 100 Institute Road, Kaven Hall, Worcester, MA 01609, United States, jeckabs@gmail.com

bWorcester Polytechnic Institute (WPI), 100 Institute Road, Kaven Hall, Worcester, MA 01609, rajib@wpi.edu

cRAP Technologies, 217 Belhaven Avenue, Linwood, NJ 08221, United States, info@raptech.us

Abstract

Dramatically rising asphalt binder cost, dwindling budgets, growing traffic loads, and the desire to find more sustainable paving practices are forcing agencies to seek ways for maximizing the re-use of Reclaimed Asphalt Pavement (RAP). While most of the academic and industrial institutions have been focused on the development of procedures to recycle hot asphalt mixes with up to 40% RAP content, a few industry innovators have refined 100% recycling technologies over the past four decades to a level where routine production of 100% recycled mixes is in clear sight. The main hindrance in the widespread use of 100% recycling is the unproven performance of 100% RAP pavements and lack of a unified and rational system for selection of materials and mix design. The objective of this research was, therefore, to critically investigate the concept of 100% recycling, determine whether such mixtures can perform as well as conventional asphalt mixes and if yes, develop a mixture design method for 100% recycled asphalt. This article presents a summary of the research, demonstrating that with adequate mixture design 100% recycled asphalt mixtures can perform equally to conventional asphalt. The available production technologies are also shortly summarized. Finally an environmental effect and cost calculation is performed demonstrating reduction of emission by 35% while reducing the costs of materials by half.

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* Corresponding author. Tel.: +37-126-665-537.
E-mail address: jeckabs@gmail.com
1. Introduction

Currently in many construction projects asphalt is recycled in unbound base layers; for road shoulders and rural roads; cold or hot in-place recycling; and by adding a relatively small percentage to new hot mix asphalt. Asphalt recycling is not truly sustainable when it is degraded and used in these lower value applications. 100% hot mix recycling closes the materials cycle by fully utilizing the valuable materials found in reclaimed asphalt in high quality application.

There are many questions and confusion among researchers and industry regarding the feasibility and necessity for production of total Reclaimed Asphalt Pavement (RAP) recycling. This paper and the complementary video (https://youtu.be/y-rYvdGiEbY) presents a summary of a holistic study to evaluate the technology, benefits, constrains, costs, and viability of 100% RAP hot mix asphalt as well as a summary of the recorded performance of such mixes.

Here introduce the paper, and put a nomenclature if necessary, in a box with the same font size as the rest of the paper. The paragraphs continue from here and are only separated by headings, subheadings, images and formulae. The section headings are arranged by numbers, bold and 10 pt. Here follows further instructions for authors.

2. History of 100% RAP Production

2.1. Historical sites

Historically, due to oil crisis in the 1970’s and consecutive increase in binder cost, a significant effort was placed on research of high use of RAP. FHWA demonstration project No.39 in the 1970’s and beginning of the 1980’s was aimed at reducing energy use and asphalt costs by maximizing the recycling. Due to the available production technologies at the time, RAP content in most projects was limited to around 30-70% (Hellriegel (1980); Howard et al. (2009); Henely (1980); Zywiak (1982); Federal Highway Administration (1995)). The few 100% RAP field research projects that could be found in the literature are listed in Table 1. The observed problems of pavement performance, consistency, production and excessive emissions at the very high RAP projects significantly reduced the research and trust in high RAP content mixtures (Howard et al. (2009); Bloomquist et al. (1993)). A comfortable approach of using low RAP content (10 to 25%) has been adopted since then and is reality even nowadays.

2.2. Modern plants

The unsuccessful initial experience with high RAP mixes in many respects can be attributed to immature production technology. Bonaquist (Bonaquist (2007)) has noted that many of the isolated failures with high RAP content mixtures have occurred when unprocessed RAP was produced in asphalt plants that were not designed to handle such mixtures.

The aim of 100% recycling was not forgotten and a numerous inventers tried to develop a technology that would allow to produce up to 100% RAP content mixtures. Many of these technologies, like Cyclean microwave heating process, were not successful in commercialization, but new designs have come in place and currently many different technologies, although most produced as pilot plants in one unit, are available (Zaumanis et al. (2014a)):

- “All-RAP process” process uses conventional hot mix asphalt plant components and a patented multi-stage filtration system to capture blue smoke.
- “Ammann RAH 100” is a counter flow dryer with two phase drum where the RAP is heated with hot air and dispatched before contact with direct flame.
• “Rapmaster” processor heats the RAP indirectly using gases that are generated in a dedicated combustion chamber and channeled inside heat exchange tubes that pass through the length of the drum in counter flow direction.
• “Astec RAP King” is a hot-oil tube type rotary drum where RAP flows across internal hot-oil filled tubes as the drum rotates.

Table 1. Historic 100% RAP plant-produced hot mix asphalt projects.

<table>
<thead>
<tr>
<th>Project</th>
<th>Construction year</th>
<th>Layer</th>
<th>Additive dose and type</th>
<th>Plant type</th>
<th>Performance</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interstate 8, Sentinel, Arizona</td>
<td>1978</td>
<td>Base and surface</td>
<td>2.5% Cyclogen</td>
<td>Central, Drum dryer</td>
<td>Likely due to overdose of rejuvenator, in-place density showed low air voids (0-2.3%) although the mixture was designed with 4.1% air voids</td>
<td>(Federal Highway Administration, 1995; Little &amp; Epps, 1980)</td>
</tr>
<tr>
<td>Interstate 15, Henderson, Nevada</td>
<td>1974</td>
<td>Surface</td>
<td>1.5% AR-8000 0.75% Paxole</td>
<td>Central, Drum dryer</td>
<td>Section required heavy maintenance and was removed in 1986</td>
<td>(Federal Highway Administration, 1995; Little &amp; Epps, 1980)</td>
</tr>
<tr>
<td>U.S. 84, Snyder, Texas</td>
<td>1976</td>
<td>Base</td>
<td>4.0% AC-10</td>
<td>Central, Hot pug mix</td>
<td>n/a</td>
<td>(Little &amp; Epps, 1980)</td>
</tr>
<tr>
<td>Loop 374, Mission, Texas</td>
<td>1975</td>
<td>Surface</td>
<td>1.6% Reclamite 3.0% AC-5 2.0% Flux oil</td>
<td>Central, Drum dryer</td>
<td>n/a</td>
<td>(Little &amp; Epps, 1980)</td>
</tr>
<tr>
<td>U.S. 50, Holden, Utah</td>
<td>1975</td>
<td>Surface</td>
<td>1.5% AC-10</td>
<td>Central, Drum dryer</td>
<td>n/a</td>
<td>(Little &amp; Epps, 1980)</td>
</tr>
<tr>
<td>Georgia</td>
<td>1991</td>
<td>Unspecified</td>
<td>0% and 4% unspecified recycling agent</td>
<td>“Cyclean”</td>
<td>Good performance after 17 months of service</td>
<td>(Bloomquist et al., 1993)</td>
</tr>
</tbody>
</table>

• “HyRAP” is a direct heating system that uses a parallel flow drum with four point material entry collars for different fractions of RAP.
• “Alex-Sin Manufacturing” uses a double shell drier where the RAP is passed through the inner shell and heated from the outer shell using seven perpendicularly located burners.
• “RATech” uses indirect heating from a separate hot air generator to heat RAP in an originally designed triangle profile drier.
• “HERA System” is an indirect heating process in which hot gasses heat the outside of satellite tubes in drum, inside which the asphalt is heated and dried while rotating.
• “Bagela” recycler is an ultra-portable (towable) drum with up to 10t/hour production capacity. Flame in a separate combustion chamber heats RAP mainly through the hot wall of mixing drum.
• “RSL” is another company producing towable recycling units with up to 25t/h capacity. In the process heat is directed into the top of the mixing drum, inside which the asphalt is heated and dried while rotating.

3. Mix design

The traditional mix design methodology, especially with respect to design of optimal binder content, has to be modified for very high content RAP mixtures. The mix designer will have to make compromises when choosing...
how to process the reclaimed asphalt and what size fractions best satisfy the mixture gradation, binder content, mixture volumetric and performance-property requirements while efficiently utilizing the available material.

Choice of recycling agent and its dose is another significant aspect. These products are designed to alter the mechanical properties and chemical composition of aged RAP binder in order to ensure the required pavement performance for another service period. They should reduce the RAP mixture stiffness and make the RAP asphalt binder effectively “available” for blending without overly softening the mix to cause rutting problem.

The authors’ proposed design principles for dense-graded high-RAP mixes can be summarized as follows (Fig.1):

- First, the aggregates are tested for the required properties and the chosen RAP fractions are combined in an initial mixture composition. The basic principle for ensuring good performing asphalt pavement is to apply the same requirements to the RAP aggregates as those that are specified for virgin mineral aggregates (Willis et al. (2012)).
- The binder is then extracted from the mixture to determine its properties and choose the necessary recycling agent type and dose. The binder content can be modified by changing RAP source, adjusting fines content in the mixture, switching between rejuvenators or modifying their dose and, finally, adding virgin binder. Care should be given to ensure diffusion and blending between rejuvenator, RAP binder and virgin binder, if any.
- The asphalt is mixed and compacted in laboratory to determine the volumetric and performance-related properties. The chosen performance-test methods should be based on the local climatic conditions, anticipated failure modes as well as the experience, confidence and availability of pass/fail criteria. These tests in some cases might have to replace the volumetric design principles.
- The steps are repeated by taking appropriate modification if correspondence to the specification requirements are not met at any stage.

A proper mix design alone will not ensure the expected pavement performance. Consistency of the end product must be ensured through management and quality control operations of reclaimed asphalt. Material supply chain including the milling, processing, storage, and quality control operations have to be an integral part of high content reclaimed asphalt production. Some of the most important operations to consider are:
• Separation of RAP having various values (aggregate or binder type, age, etc.), just like it is done with virgin aggregates;
• Minimization of fines content during milling and processing operations;
• Control and minimization of stockpile variability through sufficient material sampling, testing, as well as stockpile grading, fractionation, and mixing;
• Reduction of moisture content;
• Elimination of stockpile contamination (including startup waste).

4. Performance and test results

For being viewed as an alternative to conventional asphalt any high-RAP mixture (including 100% recycled asphalt) has to provide the expected performance and longevity of the road pavement. The main mix performance hindrances toward increased use of high content reclaimed asphalt mixtures are:

• **Cracking.** The distresses in high RAP mixtures are mostly associated with the aged binder. The stiff, less elastic binder in RAP typically increases mixture stiffness (Al-Qadi et al. (2012); West et al.(2013)) and therefore can cause fatigue damage (Daniel et al. (2010); Shah et al. (2007); West et al. (2011)) and low temperature brittleness (Terrel et al. (1992); West et al. (2011)). These are some of the main reasons for reluctance for government agencies to allow very high RAP content (Mogawer et al.(2012); Willis et al. (2012)).

• **Rutting.** Multiple studies have shown that the resistance to rutting resistance is likely to be very good for high RAP mixes because of the presence of aged binder (McDaniel et al. (2000); Silva et al. (2012); Karlsson et al. (2006)). However, the recycling agents are aimed at reduction of the mix stiffness and may cause increased rutting if overdosed or insufficiently diffused in RAP binder.

• **Flushing.** In field studies with the use of incompatible products or excessive dose of recycling agents, a migration of oils toward the surface of the asphalt layer has been noticed, resulting in reduction of the friction of wearing course and compromised pavement performance. This has been described as unstable rejuvenation resulting in bleeding or flushing (Karlsson et al. (2006); Kandhal et al. (1997)).

4.1. 100% recycling research result overview

To evaluate the performance of 100% RAP mixture in respect to the problems mentioned above, a research was performed and short summary of the main results is presented here and in a video https://youtu.be/y-rYvGiEbY.

**Rejuvenator screening** (Zaumanis et al. (2013b)). The research was started with a screening study of rejuvenators. Nine different products were mixed with extracted RAP binder, including plant oils, waste-derived oils, engineered products, as well as traditional and non-traditional refinery base oils. The efficiency of softening the aged RAP binder by these rejuvenators was evaluated through testing of kinematic viscosity and penetration and results demonstrated that six of the oils can ensure sufficient reduction of viscosity. Low temperature creep compliance and tensile strength tests of mixture demonstrated that all products provided similar or reduced stiffness compared to unmodified RAP mixture, but only five of them ensured equal or higher strength. The products that provided improvement in all tests were refined tallow, aromatic extract, distilled tall oil and organic blend.

**Performance properties** (Zaumanis et al. (2014c), Zaumanis et al. (2014d)). After validation of the general concept, a thorough study to determine the performance properties of 100% recycled asphalt pavement was undertaken. Six rejuvenators were used in the study: waste vegetable oil, waste vegetable grease, organic oil, distilled tall oil, aromatic extract, and waste engine oil. These products were added at a 12% dose to a 100% RAP mixture that was re-graded to correspond to Superpave 9.5mm requirements. The mixtures were compared with unrejuvenated RAP mixture and a virgin mix with the same gradations. The main findings were that (1) rutting resistance of rejuvenated mixes was excellent and correlates well with performance grade of bitumen; (2) five of the six rejuvenators reduced low temperature cracking susceptibility compared to RAP mix and two rejuvenators provided similar performance to virgin mix; (3) fatigue was measured using three different tests: Linear Amplitude Sweep (LAS) for binder, as well as Coaxial Sheer Test (CAST) and Fracture Work Density (FWD) for mixture. The 100% rejuvenated mixes demonstrated mixed performance in comparison with the virgin mix and the test results
varied depending on the test method and loading conditions. (4) moisture resistance was good for all of the rejuvenated samples, but some plant oil products had the tendency to decrease it. (5) rejuvenators improved the mix workability, but not to a level of the virgin mix;

**Rejuvenator dose optimization** (Zaumanis et al. (2014b)). A study was undertaken to develop a practical method to determine an optimum rejuvenator dose that would enable the designer to ensure reduced stiffness and improved resistance to cracking without over softening the binder to cause rutting. To evaluate the overall trends two doses of six rejuvenators were added to the recovered RAP binder and they were tested for performance grade (PG), and penetration. The study showed that for all of the rejuvenators the high and low PG temperature were reduced linearly with an increased dose while penetration increased exponentially. It was found that the PG sum of aged-rejuvenated binder is likely to be higher than that of source virgin binder. These findings were taken into account and an outline for optimizing the rejuvenator dose was developed to account for the variability of the RAP binder due to differences in aging and RAP source.

**Micro-mechanics and rheology** (Yu X et al. (2014)). A study focusing on fundamental aspects of rejuvenation was undertaken. Two different bitumens were artificially aged and rejuvenated by blending with two rejuvenators (aromatic extract and waste vegetable oil). The blends were tested using bending beam rheometer (BBR), atomic force microscopy (AFM) and SARA fractionation. The results indicated that mechanical properties of rejuvenated binders were in between those of virgin and aged binders and this was qualitatively consistent with microscopic measurements of adhesion and dissipation of the same binders. The alterations in mechanical properties were well reflected in changes of chemical composition according to SARA fractionation results. Aging of binders demonstrated significant morphological transformations but rejuvenation most often did not reproduce the original microstructure of virgin binder.

**Modelling of rejuvenator diffusion** (Zaumanis et al. (2013a)). Stoke-Einstein’s equation and Fick’s law were used as the basis of calculations with finite element method that was aimed at determining the effect of time and temperature on rejuvenator diffusion in binder film. The results helped in estimation of the temperature range to reach homogeneous rejuvenator concentration within binder film during production; it also demonstrated the complexity of bitumen and rejuvenator interaction since the results were not fully in line with mechanical test results.

**Full scale trials.** To evaluate moisture susceptibility, samples were cored from 100% RAP pavement on 154th street between 25th and 26th avenue in Queensborough, NYC, shortly after paving in 2011, and repeatedly at the same locations in 2013 (Fig. 2). The samples that were cored shortly after construction confirmed that pavement has the targeted 7.0% air voids. After two years of service the asphalt pavement had further densified having average air voids from six cores of 3.5 % (range 2.0-4.8 %). These cored samples were tested for Tensile Strength Ratio (TSR) after conditioning using Moisture Induced Stress Test (MIST). This device simulates conditions of repeated pore pressure in saturated pavement created by moving vehicle tires. MIST consists of a system to use a supply of compressed air to load and apply vacuum to force water out and in through an HMA sample. The conditioning was run according to ASTM D7870 procedure, having 5000 cycles of loading with water pressure of 0.28 MPa at 40 °C.

![Fig. 2. Coring of 100% RAP samples in 2013.](image)
In addition, samples were produced from the same materials in the laboratory providing a total of three sets of samples:

- Plant-mixed, road-compacted: samples obtained from road cores.
- Plant-mixed, laboratory-compacted: mixture was sampled during production and compacted after reheating in laboratory.
- Laboratory-mixed, laboratory-compacted: materials were sampled during production and both mixed and compacted according to the same mix design in laboratory.

Before determining tensile strength, half of the samples were exposed to MIST while the other half was tested dry. The TSR values in Table 2 demonstrates the strength of dry versus moisture conditioned samples. The TSR is high for all samples, having no loss of strength after moisture conditioning. Thus all samples well exceed the traditional requirement of saturated to dry strength ratio of 0.8. The tensile strength of laboratory mixed, laboratory compacted samples was the highest of all mixtures. It has to be noted that road cores were 10 cm while lab-produced specimens were 15 cm in diameter. One other parameter indicating moisture damage is a significant change (more than 1.25 %) in bulk specific gravity (BSG) after MIST test, but as demonstrated in the table none of the samples experienced such problem. Thus the experiment confirms that there is no moisture damage, and the moisture susceptibility results can be accurately predicted in laboratory.

Table 2. Tensile Strength Ratio for Differently Prepared Samples.

<table>
<thead>
<tr>
<th>Sample Type</th>
<th>Dry air voids, %</th>
<th>BSG change after MIST, %</th>
<th>Dry tensile strength, kPa</th>
<th>Average TSR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Road cores after 2 year service</td>
<td>3.5</td>
<td>-0.43</td>
<td>440</td>
<td>0.99</td>
</tr>
<tr>
<td>Plant-Mixed, Laboratory-Compacted</td>
<td>7.0</td>
<td>0.0</td>
<td>439</td>
<td>1.01</td>
</tr>
<tr>
<td>Laboratory-Mixed, Laboratory-Compacted</td>
<td>5.9</td>
<td>-0.66</td>
<td>540</td>
<td>1.02</td>
</tr>
</tbody>
</table>

The good performance of 100% RAP mixtures is further confirmed in a study by Mallick et al. (2010). The authors present results of full scale application of 100% RAP wearing coarse in New York City. Renoil™ recycling agent was used to restore the RAP binder grade to the desired PG 70-28 grade for 12.5mm Suparpave dense-graded asphalt mixture. The results demonstrated good consistency of air voids, Marshall stability and flow. Samples were also cored from 7 year old 100% RAP pavement where Renoil was used as recycling agent. The air void content at four of six core locations was similar to control section while at the others two it was high (9.6 and 11.2%). Stiffness of the rejuvenated 100% RAP mixture, measured by resilient modulus test, was lower than that of concurrently paved 15% RAP mixture that was used as control. Creep compliance at -10°C, which is an indicator of low temperature stiffness, showed similar results for both 15% and 100% RAP mixtures.

Finally, a visual inspection tour of the first 100% recycled sites in New York City was performed in 2012. Wearing courses on 85th road and 75th street in Woodhaven were constructed in 2001 along with control sections. The mixtures had 12.5 mm design (6F mixture designation by NYC DOT) and were paved on a concrete base. The inspection did not reveal significant differences between the virgin control sections and 100% recycled asphalt pavement and both sections were performing well.

5. Environmental Analysis

For hot mix pavements, the main two main processes that are responsible for GHG emissions and energy use are binder and asphalt mix production (Chappat et al. (2003); Huang et al. (2009)). RAP use reduces the binder consumption and thus proportionally decreases the environmental effect. To determine the effect of 100% recycling a calculation was performed that is described in full in Zaumanis et al. (2014a). Because of the lack of long term in-field performance, the analysis was limited to unit inventory or cradle-to-gate analysis.
The emissions data from different processes of asphalt production was compiled from four different sources. Based on “Re-Road” project (Waymen et al. (2012)) and the practical experience reported by 100% RAP mixture producers, the energy use at asphalt production and paving operations was assumed to be independent of recycled asphalt content rate. According to the developers of the recycling technologies, the emissions were also assumed similar to traditional asphalt plants (RAP Technologies; RAP Process Machinery; Volker Wessels). A mixture containing 25% sand, 70% crushed stone and 5% bitumen was used in the calculations as a representation of a typical virgin mix. 100% RAP mixture is considered having a recycling agent content of 12% by binder mass.

The estimation of cradle-to-gate emissions of virgin mix versus 100% RAP mixture, including raw material production, RAP processing, asphalt production, hauling and paving is presented in Fig. 3. For simplicity, the transport distance was considered constant and consists of 50 km distance from quarry/RAP site to asphalt plant plus 50 km asphalt plant to paving site. The only variables in the process are energy use for production of constituent materials. The calculation results demonstrate 18 kg or 35% of CO2 equivalent reduction per ton of paved mixture when producing asphalt from 100% reclaimed material instead of using virgin material.

6. Cost Analysis

A calculation was performed to assess the materials related costs for production of mixtures with increased RAP content. Material prices in New Jersey, US from the middle of 2014 were used for calculation. These expenses will vary in time and depend on the technology in use and the location of the contractor. For example, large metropolitan areas often have surplus of RAP from city streets and the contractors will often pay for disposing it. Rural areas, on the other hand may have shortage of RAP and asphalt producers will need to purchase it. The operational expenses that are likely to remain constant (e.g. staff wages, rent) were not included in the calculation.

For calculation purposes a mix design having aggregate content of 94.3% and binder content of 5.7% (RAP binder 5.1% + recycling agent 0.6%) was used.

Fig. 4 summarizes the calculation results of material related costs per ton of produced asphalt with a RAP content ranging from 0% to 100% RAP. Depending on the market situation with availability of RAP, the costs of per ton of 100% RAP mixture would be reduced between 50 to 70% compared to virgin mix.
7. Summary and Discussion

Dramatically rising bitumen cost, dwindling budgets, growing traffic loads, and the desire to find more sustainable paving practices are forcing agencies to seek ways for maximizing the re-use of Reclaimed Asphalt Pavement (RAP). While most of the academic and industrial institutions have been focused on the development of procedures to recycle hot asphalt mixes with up to 40% RAP content, a few industry innovators have refined 100% recycling technologies over the past four decades to a level where routine production of 100% recycled mixes is in clear sight.

A doctoral study was undertaken with an objective to critically investigate the concept of 100% recycling, determine whether such mixtures can perform as well as conventional asphalt mixes and if yes, develop a mixture design method for 100% recycled asphalt.

The research work began with an extensive review of the existing production technologies and quality control procedures for hot-mix recycling. It was found that there are at least ten readily available, but sparingly used, production technologies for 100% hot-mix recycling and they were described in detail. One of them – RAP Technologies (located in New York City) – was collaborating with WPI for developing the research.

The study involved testing of eleven rejuvenators both to restore binder properties and in 100% RAP lab-produced mixtures. A methodology was developed to optimize the rejuvenator content for ensuring the desired Performance Grade (PG) with proper consideration of the statistical variability of RAP stockpile. Extensive rheological, micromechanical and chemical characterization tests were performed with select rejuvenators to confirm true rejuvenation of aged binders. The final proof of rejuvenation was a series of 100% RAP mix tests. The results indicated that with appropriate mix design and choice of rejuvenators, significant improvement in low temperature cracking resistance while providing a moisture and rut resistant mixture. With the use of some rejuvenators a long-term performance equal to that of reference virgin mix was achieved. Based on these findings a framework for designing 100% recycled asphalt mixtures was developed.

A cradle-to-gate analysis of environmental effects indicated 35% CO₂eq savings of a 100% RAP asphalt mixture compared to virgin mix. Cost analysis showed at least 50% savings in material related expenses.

Full results of the study are available in seven articles and are summarized in a video (https://youtu.be/y-rYvdGiEbY).

Based on the proven experience with the 100% recycled pavement in city streets and excellent research results, the New York City department of transportation has allowed paving of such mixtures in the city streets since 2015!

8. References


Binder and 100 % recycled asphalt Mixtures. Construction and Building Materials 71: 538-550, DOI: 10.1016/j.conbuildmat.2014.08.073


