Performance-Related Mix Design and Balanced Mix Design

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- Dan Karcher, R.E. Pierson
Presentation Overview

- Introduction
- Guideline to Developing Performance Related Specifications (PRS) for HMA
  - Identifying needs
  - Baseline/target development
  - Sampling/Testing Protocols
- Current “Northeast” Practices
- Balanced Mix Design – The Future
- Summary/Conclusions
Performance-Based: Quality Assurance specifications that describe the desired levels of fundamental engineering properties that are predictors of performance and appear in primary prediction relationships
- Resilient modulus, creep properties, fatigue properties
- Models that can be used to predict pavement stress, distress, or performance

Performance-Related: Quality Assurance specifications that describe the desired levels of key materials and construction quality characteristics that have been found to correlate with fundamental engineering properties that predict performance
- Air voids for HMA; Compressive strength for PCC
- HMA performance testing(?)
Currently a concern among state agencies that current volumetric mixture design does not ensure good field performance

Depending on climate, traffic, pavement conditions, different state agencies require different levels of performance

- Not all HMA is created equal
  - New Jersey – rutting, fatigue cracking, reflective cracking
    - Different criteria required for different mix type, location in pavement, and pavement type
Guideline to Developing Performance Related Specifications (PRS)
Guidelines for Developing PRS

- Know your pavement performance
- Develop a baseline for performance
- Select an appropriate test procedure
- Develop testing & specification structure
- Go back and re-evaluate
Important to recognize pavement issues
Testing methods should try to simulate distress types found in the field
  - Rutting, fatigue cracking, reflective cracking, thermal cracking
    - Mode of failure should be used in the lab
    - Test temperatures should model climate conditions

Example:
  - New Jersey: Fatigue Cracking
    - Bridge Deck Mix – uses Flexural Beam fatigue
    - Bituminous Rich Intermediate Course – use Overlay Tester
Develop a Performance Baseline

- How would you like your materials to perform?
  - Historical field data (PMS)
  - Database of material properties
  - Performance criteria should be developed using the performance of local materials
    - Try to avoid “adopting” other state’s specifications when you do not have history of local material performance
- New Jersey Example: High RAP Specification
  - Performance criteria based on virgin (0% RAP) mix
- NYCDOT: High RAP Specification
  - Developing performance criteria based on 30% RAP mix (30% RAP is minimum NYC must use)
Select Appropriate Test Procedure

- Priorities of test procedure
  - Correlates to field performance
  - Sensitivity to mixture properties
  - Repeatability
  - Ease of use (procedure, test specimen, time and analysis)
  - Availability/Cost
- NCHRP 9-57 Study – Mixture Cracking Tests

<table>
<thead>
<tr>
<th>Thermal cracking tests</th>
<th>Reflection cracking tests</th>
<th>Fatigue cracking tests</th>
<th>Top-down cracking tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. DCT</td>
<td>1. OT</td>
<td>1. Beam fatigue</td>
<td>1. IDT-Florida</td>
</tr>
<tr>
<td>2. SCB-IL</td>
<td>2. SCB-LTRC</td>
<td>2. SCB-LTRC</td>
<td>2. SCB-LTRC</td>
</tr>
<tr>
<td>3. SCB (AASHTO TP105)</td>
<td>3. BBF</td>
<td>3. OT*</td>
<td></td>
</tr>
</tbody>
</table>

*OT for fatigue cracking was added later by request of the panel.
Example: New Jersey

- Rutting: Asphalt Pavement Analyzer (AASHTO T340)
- Fatigue Cracking:
  - Bridge Decks – Flexural Beam Fatigue (AASHTO T321)
  - BRIC, HRAP – Overlay Tester (NJDOT B-10; TxDOT Tx-248F)

Rt 80 in New Jersey

- 2015 construction
- NJDOT HPTO mixture
- Testing indicated 1st 4 nights’ production failed rutting criteria
### Example: New Jersey HPTO – AASHTO T340

<table>
<thead>
<tr>
<th>Date</th>
<th>APA (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5/27/2015</td>
<td>6.56</td>
</tr>
<tr>
<td>5/28/2015</td>
<td>6.23</td>
</tr>
<tr>
<td>5/29/2015</td>
<td>6.5</td>
</tr>
<tr>
<td>6/3/2015</td>
<td>6.84</td>
</tr>
<tr>
<td>6/4/2015</td>
<td>3.66</td>
</tr>
<tr>
<td>6/5/2015</td>
<td>3.87</td>
</tr>
<tr>
<td>6/9/2015</td>
<td>3.92</td>
</tr>
<tr>
<td>6/10/2015</td>
<td>4.32</td>
</tr>
<tr>
<td>6/11/2015</td>
<td>3.98</td>
</tr>
<tr>
<td>6/12/2015</td>
<td>3.73</td>
</tr>
<tr>
<td>6/17/2015</td>
<td>3.83</td>
</tr>
<tr>
<td>6/18/2015</td>
<td>2.94</td>
</tr>
<tr>
<td>6/19/2015</td>
<td>2.73</td>
</tr>
<tr>
<td>6/24/2015</td>
<td>3.99</td>
</tr>
</tbody>
</table>

![Graph showing average rutting (inches) vs. milepost](image.png)
Select Appropriate Test Procedure

- Be careful of adopting test methods and criteria developed by other agencies
  - Should you consider a rutting and fatigue cracking to “balance” performance?
- Be careful of selecting test procedures where results may be dependent on multiple failure mechanisms
  - Example: Hamburg Wheel Tracking (TxDOT) for rutting
    - Running test under water couples stripping and rutting – which mode of distress dominates?
Ex. - Hamburg: Rutting or Stripping or Both?

Same test temperature
Different performance

(Reinke, 2016)
Develop Specification Structure

- Stage of testing
  - Should it be included during mix design? Test strip? QC/QA?
- Frequency of testing
  - Lot, night’s production?
  - Keep in mind time requirements of the test method
- Responsible testing laboratory
  - State lab, consultant, university partner, asphalt plant under state inspection
  - AMRL accreditation required?
- Handling failing results
  - Remove/replace, pay adjustment, stop production to adjust mix
Example: New Jersey

- Testing conducted;
  - During mix design, required test strip, 1\textsuperscript{st} and every other Lot
    - Small production quantities are tested once per night production
  - Testing laboratory;
    - Up to 1/2016 – University Partner (Rutgers – AMRL Accredited)
    - 1/2016 – Present – NJDOT Central Laboratory
- Handling failing results
  - Mix design – must conduct redesign until passes
  - Test strip – must conduct another test strip until passes
  - Mainline – pay adjustment (negative only at this time)
## Table 902.11.04-2 Performance Testing Pay Adjustments for HMA HIGH RAP

<table>
<thead>
<tr>
<th></th>
<th>Surface Course</th>
<th></th>
<th>Intermediate Course</th>
<th></th>
<th>PPA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PG 64-22</td>
<td>PG 76-22</td>
<td>PG 64-22</td>
<td>PG 76-22</td>
<td></td>
</tr>
<tr>
<td>APA @ 8,000 loading cycles, mm (AASHTO T 340)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>t ≤ 7</td>
<td>t ≤ 4</td>
<td>t ≤ 7</td>
<td></td>
<td>t ≤ 4</td>
<td>0</td>
</tr>
<tr>
<td>7 &gt; t &gt; 10</td>
<td>4 &gt; t &gt; 7</td>
<td>7 &gt; t &gt; 10</td>
<td></td>
<td>4 &gt; t &gt; 7</td>
<td>– 1</td>
</tr>
<tr>
<td>t ≥ 10</td>
<td>t ≥ 7</td>
<td>t ≥ 10</td>
<td></td>
<td>t ≥ 7</td>
<td>– 5</td>
</tr>
<tr>
<td>Overlay Tester, cycles (NJDOT B-10)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>t ≥ 150</td>
<td>t ≥ 175</td>
<td>t ≥ 100</td>
<td></td>
<td>t ≥ 125</td>
<td>0</td>
</tr>
<tr>
<td>150 &gt; t &gt; 100</td>
<td>175 &gt; t &gt; 125</td>
<td>100 &gt; t &gt; 75</td>
<td></td>
<td>125 &gt; t &gt; 90</td>
<td>– 1</td>
</tr>
<tr>
<td>t ≤ 100</td>
<td>t ≤ 125</td>
<td>t ≤ 75</td>
<td></td>
<td>t ≤ 90</td>
<td>– 5</td>
</tr>
</tbody>
</table>
Go Back and Re-evaluate

1. Task or Idea Identification/Modification
2. Modification of Procedures/Specifications
3. Focused Research & Evaluation
4. Application/Pilot Project Studies
5. Results Analysis/Spec Development

The cycle shows a continuous process of developing and refining ideas through research and evaluation, followed by application and analysis, and then going back to refine further.
“Northeast” States Survey Performance Related Specs
Brief email survey sent out to “Northeast” states regarding current/potential use of PRS

1. Is your state using PRS, and if so, at what level?
2. Who conducts the testing?
3. What pavement distresses are you concerned with?
4. What performance tests are you using?
5. What types of asphalt mixtures are you using PRS?

States responding
- 8 Northeast (CT, DE, NH, NJ, NY, PA, RI, VT) + Missouri
At what level is your state using PRS?

- 2 states using/developing PRS solely for mixture design acceptance
- 1 state using/developing PRS for mixture design and Quality Acceptance
- 2 states using/developing PRS for quality acceptance
- 2 states still working on PRS
- 2 states not interested at the moment
Who is/would be responsible for testing within your PRS?

- 3 states using solely their agency laboratory
- 1 state combining agency and consultant services
- 2 states combining agency and university partner
- 1 state requiring contractor to hire accredited laboratory
What pavement distresses are you most concerned with?

- Fatigue cracking (7 states)
- Thermal cracking (6 states)
- Rutting (5 states)
Performance tests you are using/considering?

- Rutting
  - Hamburg Wheel Tracking: 3 states
  - Asphalt Pavement Analyzer: 2 states
  - AMPT Flow Number: 1 state

- Fatigue cracking
  - Semi-circular Bend (SCB): 3 states
  - Overlay Tester: 2 states
  - Flexural Beam Fatigue: 2 states

- Thermal cracking
  - Disc Compact Tension (DCT): 1 state
### Performance tests you are using/considering?

<table>
<thead>
<tr>
<th>Mix Design</th>
<th>Quality Control</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Rutting</strong></td>
<td></td>
</tr>
<tr>
<td>Flow Number</td>
<td></td>
</tr>
<tr>
<td>APA</td>
<td>Rutting</td>
</tr>
<tr>
<td>Hamburg</td>
<td></td>
</tr>
<tr>
<td><strong>Fatigue Cracking</strong></td>
<td></td>
</tr>
<tr>
<td>Flexural Beam</td>
<td>Flexural Beam</td>
</tr>
<tr>
<td>Overlay Tester</td>
<td></td>
</tr>
<tr>
<td>SCB</td>
<td></td>
</tr>
<tr>
<td><strong>Thermal Cracking</strong></td>
<td></td>
</tr>
<tr>
<td>N.A.</td>
<td>Thermal Cracking</td>
</tr>
<tr>
<td><strong>N.A.</strong></td>
<td></td>
</tr>
</tbody>
</table>
What types of asphalt mixtures are you concentrating PRS on?

- Specialty mixes (High RAP, Bridge Deck, etc): 3 states
- High traffic volume: 1 state
- When job requires > 6000 tons: 1 state
- All HMA: 1 state
The Future – Balanced Mix Design
History of Mixture Design

1890
- Barber Asphalt Paving Company
  - Asphalt cement 12 to 15% / Sand 70 to 83% / Pulverized carbonite of lime 5 to 15%

1905
- Clifford Richardson, New York Testing Company
  - Surface sand mix: 100% passing No. 10, 15% passing No. 200, 9 to 14% asphalt
  - Asphaltic concrete for lower layers, VMA terminology used, 2.2% more VMA than current day mixes or ~0.9% higher binder content

1920s
- Hubbard Field Method (Charles Hubbard and Frederick Field)
  - Sand asphalt design
  - 30 blow, 6” diameter with compression test (performance) asphaltic concrete design (Modified HF Method)

1927
- Francis Hveem (Caltrans)
  - Surface area factors used to determine binder content; Hveem stabilometer and cohesometer used
  - Air voids not used initially, mixes generally drier relative to others, fatigue cracking an issue

1943
- Bruce Marshall, Mississippi Highway Department
  - Refined Hubbard Field method, standard compaction energy with drop hammer
  - Initially, only used air voids and VFA, VMA added in 1962; stability and flow utilized

1993
- Superpave
  - Level 1 (volumetric)
  - Level 2 and 3 (performance based, but never implemented)
Balanced Mixture Design (BMD)

Superpave Mixture Design

Rutting  Cracking
Get as much asphalt binder in the mixture to improve the Durability until the Stability of the mixture is no longer acceptable. Somewhere in the middle the mix is “balanced”!

(Hveem, 1940)
Four Steps for Superpave Mix Design

1. Materials Selection
2. Design Aggregate Structure
3. Design Binder Content
4. Moisture Sensitivity

TSR
Volumetric Design Criteria

Table 902.02.03-2 Gyratory Compaction Effort for HMA Mixtures

<table>
<thead>
<tr>
<th>Compaction Level</th>
<th>ESALs(^1) (millions)</th>
<th>(N_{des})</th>
<th>(N_{max})</th>
</tr>
</thead>
<tbody>
<tr>
<td>L</td>
<td>&lt; 0.3</td>
<td>50</td>
<td>75</td>
</tr>
<tr>
<td>M</td>
<td>(\geq 0.3)</td>
<td>75</td>
<td>115</td>
</tr>
</tbody>
</table>

\(^1\) Design ESALs (Equivalent (80kN) Single-Axle Loads) refer to the anticipated traffic level expected on the design lane over a 20-year period.

Table 902.02.03-3 HMA Requirements for Design

<table>
<thead>
<tr>
<th>Compaction Levels</th>
<th>Required Density(% of Theoretical Max. Specific Gravity)</th>
<th>Voids in Mineral Aggregate (VMA),% (minimum)</th>
<th>Voids Filled With Asphalt (VFA)(^1) %</th>
<th>Dust-to-Binder Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(@N_{des})^ 2 &amp; (@N_{max})</td>
<td>Nominal Max. Aggregate Size, mm</td>
<td>37.5 &amp; 25.0 &amp; 19.0 &amp; 12.5 &amp; 9.5 &amp; 4.75</td>
<td>70 - 80 &amp; 0.6 - 1.2</td>
</tr>
<tr>
<td>L</td>
<td>96.0 &amp; (\leq 98.0)</td>
<td>11.0 &amp; 12.0 &amp; 13.0 &amp; 14.0 &amp; 15.0 &amp; 16.0</td>
<td>65 - 78 &amp; 0.6 - 1.2</td>
<td></td>
</tr>
<tr>
<td>M</td>
<td>96.0 &amp; (\leq 98.0)</td>
<td>11.0 &amp; 12.0 &amp; 13.0 &amp; 14.0 &amp; 15.0 &amp; 16.0</td>
<td>65 - 78</td>
<td>0.6 - 1.2</td>
</tr>
</tbody>
</table>

Volumetrics are only used as a surrogate for performance testing.
NJDOT Balanced Mixture Design – Proof of Concept
Hypothesis: Asphalt mixtures should be designed to optimize performance, not around a target air void content

Use as much asphalt to ensure durability before stability (rutting) is an issue

Similar to conventional mix design process:
- Start at dry AC content
- Add asphalt at 0.5% increments – measure rutting and cracking
- Determine AC range where rutting and cracking are optimized
- Conduct volumetric work to compliment performance
Proof of Concept – Design Approach

- Evaluated 8 approved NJDOT surface course mixtures
  - 9.5 and 12.5 NMAS mixes
  - PG64-22 (64S) and PG76-22 (64E) binders
  - Trap Rock aggregate; Granite/Gneiss aggregate
  - 15% RAP
  - Evaluated Balanced Design (rutting vs cracking) at different AC%
- Determine Balanced Design Air Voids at the Balanced asphalt content
Balancing Design – Performance Criteria/Thresholds

- Criteria: performance criteria established by testing a large number (and variety) of sampled loose mix. Criteria based on:
  - Location in pavement (surface or intermediate/base)
  - Traffic (Low = PG64-22; Moderate to High = PG76-22)

<table>
<thead>
<tr>
<th>Test</th>
<th>Surface Course</th>
<th>Intermediate Course</th>
</tr>
</thead>
<tbody>
<tr>
<td>APA @ 8,000 loading cycles (AASHTO T 340)</td>
<td>&lt; 7 mm</td>
<td>&lt; 4 mm</td>
</tr>
<tr>
<td>PG 64-22</td>
<td>PG 76-22</td>
<td>PG 64-22</td>
</tr>
</tbody>
</table>
| Overlay Tester (NJDOT B-10)             | > 150 cycles   | > 175 cycles        | > 100 cycles        | > 125 cycles
9.5M64, Source #1 - Balanced

- **APA Rutting (mm)**
- **Overlay Tester Fatigue (cycles)**
- **Optimum AC% (JMF)**

**Area of Balanced Performance**: 5.2 - 5.9%
12.5M64, Source #1 - Balanced

![Graph showing Asphalt Pavement Analyzer Rutting and Overlay Tester Fatigue (cycles) vs. Asphalt Content (%). The area of balanced performance is highlighted between 5.2% and 5.8%.](image-url)
9.5M76, Source #1 - Balanced
12.5M76, Source #1 - Balanced

[Graph showing asphalt content (%), APA Rutting (mm), Overlay Tester Fatigue (cycles), and Optimum AC% (JMF). The area of balanced performance is indicated as 5.5 - 6%.]
### Optimum Asphalt Content Summary

<table>
<thead>
<tr>
<th>Mix Type (Supplier #1)</th>
<th>Volumetric Optimum AC% (N_{\text{des}} = 75)</th>
<th>Balanced Mix Design</th>
<th>Optimum AC (%)</th>
<th>Air Voids @ AC% (N_{\text{des}} = 75) gyrations</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1, 9.5M64</td>
<td>5.0</td>
<td></td>
<td>5.2 - 5.9 (5.6%)</td>
<td>2.8</td>
</tr>
<tr>
<td>#1, 9.5M76</td>
<td>5.0</td>
<td></td>
<td>5.1 - 5.6 (5.4%)</td>
<td>3.9</td>
</tr>
<tr>
<td>#1, 12.5M64</td>
<td>5.1</td>
<td></td>
<td>5.2 - 5.8 (5.5%)</td>
<td>3.0</td>
</tr>
<tr>
<td>#1, 12.5M76</td>
<td>5.1</td>
<td></td>
<td>5.5 - 6.0 (5.8%)</td>
<td>3.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mix Type (Supplier #2)</th>
<th>Volumetric Optimum AC% (N_{\text{des}} = 75)</th>
<th>Balanced Mix Design</th>
<th>Optimum AC (%)</th>
<th>Air Voids @ AC% (N_{\text{des}} = 75) gyrations</th>
</tr>
</thead>
<tbody>
<tr>
<td>#2, 9.5M64</td>
<td>5.4</td>
<td></td>
<td>5.2 - 5.9 (5.6%)</td>
<td>2.9</td>
</tr>
<tr>
<td>#2, 9.5M76</td>
<td>5.4</td>
<td></td>
<td>5.8 - 6.0 (5.9%)</td>
<td>3</td>
</tr>
<tr>
<td>#2, 12.5M64</td>
<td>4.6</td>
<td></td>
<td>5.1 - 6.1 (5.6%)</td>
<td>2.8</td>
</tr>
<tr>
<td>#2, 12.5M76</td>
<td>4.6</td>
<td></td>
<td>5.6 - 6.1 (5.9%)</td>
<td>3.4</td>
</tr>
</tbody>
</table>

Ave = **3.3%**

Ave = **3.0%**
Recommending Optimum AC%

- How to recommend optimum AC%?
  - Center of range?
  - High end of range for increased fatigue resistance (Hveem)?

- How to recommend production tolerances?
  - Target center of range and maintain Balanced Design Optimum AC% ranges
  - Target center and use the lesser of the following:
    - Balanced Design AC% range
    - Current production tolerance of +/-0.35%

- Does range in AC% indicate “robustness” of the mix?
Balanced Design Approach indicating that most mixes evaluated to date are designed and produced dry of “Balanced Area” in NJ

- Durability/cracking largest issue in NJ
- Resultant Balanced AC% would result in compacted air voids around 3% @ 75 gyrations, but varies based on mixture type

- Changes in current production volumetrics most likely required for implementation
- Methodology for selecting “optimum AC%” needed
Balanced Mixture Design (BMD)

- Additional information
  - FHWA ETG developing TechBrief to provide information on BMD to help provide guidance
    - Going through final editing

Balanced Mixture Design Approaches for Asphalt Pavement Construction

This Technical Brief provides an overview of balanced mixture design (BMD) approaches currently used by states in asphalt pavement construction. These approaches are still under development and this document will attempt to show the current status and some of the issues that will need to be addressed in the future.

BMD is a process to increase the probability that asphalt mixtures have the proper combination and quality of components to resist premature deterioration from pavement distresses mostly focused on rutting, cracking and moisture damage. The BMD process seeks to achieve the combination of binder, aggregate and mixture proportions that will pass established performance tests criteria for permanent deformation and cracking types for a given level of traffic, climate, and pavement structure.

The need for performance testing has increased in recent years with the introduction of new binder additives and increased use of recycled materials. It is important for state highway agencies (SHAs) and the asphalt industry to recognize the need to incorporate performance testing into asphalt mixture design to help ensure longer pavement life.

Although mixture design is one component for achieving longer pavement life, acceptance specifications are also important. While this Technical Brief will primarily focus on the mixture design, limited information will be provided regarding acceptance during construction due to its importance.
QC Lab Tools – Performance Testing for the Suppliers
Performance Testing for the Suppliers

- Rutgers University working on putting together a set of performance tests (rutting and cracking) that can be used by asphalt plants
  - Time for testing and analysis
  - Relation to current test methods/field performance
  - Cost (equipment, supplies)
Most plants still have Marshall equipment
- TSR’s
- FAA work

Proposing the use of Marshall equipment as the loading frame for new tests
High temperature IDT

- Uses TSR IDT frame with Lottman head (used for TSR)
- Gyratory compacted samples (set air void level to desired)
- Condition in oven for >4 hours; water for >2 hours
- 50 mm/min deformation rate
- Test temperature based on local climate (NCHRP 9-33 recommendations)
  - For NJ = 44°C
- Proposed by NCHRP 9-33 project
Rutgers Proof of Concept

- Compared sampled loose mix from PANYNJ projects
  - High Temperature IDT @ 44°C
  - APA Testing @ 64°C
- Relationship?

\[
y = 127.5x - 0.775 \\
R^2 = 0.5343
\]
QC Lab Testing – Fatigue – SCB Flexibility Index

- Semi-circular Bend Flexibility Index Test
  - Can use Marshall equipment
  - Modification to Lottman Head fixture required
  - 3 point bending fixture required ($600)
  - 25°C
  - 50 mm/min deformation rate

- SCB Flexibility Index found to be correlated to Overlay Tester and field cracking performance
SCB Flexibility Index

Flexibility Index (FI) = A \times G_F \times \frac{1}{|m|}

Load (kN)

Displacement (mm)

Peak Load

Opening at Peak Load ($w_0$)

Slope at inflection point ($m$)

Critical Displacement ($w_1$)
SCB Using Marshall Machine
SCB Flexibility Index
Rutgers Proof of Concept

- Compared sampled loose mix from PANYNJ projects
  - SCB Flexibility Index @ 25°C
  - Overlay Tester @ 25°C
- Relationship?

\[ y = 6.0709e^{0.0012x} \]
\[ R^2 = 0.6799 \]
Laboratory tests available for asphalt suppliers to provide help in design and material evaluation
- Not intended for acceptance (not yet anyway)
- Ultimately acceptance would continue to be conducted with APA (rutting) and Overlay Tester (fatigue) until more experience gained
- Rutting: greater than 45 psi for high temp IDT
- Fatigue cracking: greater 8 for Flexibility Index
Thank you for your time! Questions?

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