TECHNICAL UNIVERSITY OF CONSTRUCTION BUCHAREST

PHD THESIS SUMMARY

"CONTRIBUTIONS TO ASPHALT RESEARCH ON PERFORMANCE CRITERIA"

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1. INTRODUCTION. The necessity and timeliness of the PhD thesis topic

The PhD thesis addresses the issue of performance-based design of asphalt mixtures, an area in the process of harmonization of Romanian regulations (AND 605) with European standards (SR EN 13108-5). In the context of increasing demands on the durability and sustainability of road infrastructure, the thesis highlights the urgent need to technically and scientifically substantiate advanced characterization methods capable of simulating real traffic and climate conditions in Romania.

The specific objectives of the PhD thesis are:

1. **Analysis of the technical provisions of AND 605 and SR EN 13108-5**, with the identification of current limitations in the evaluation of asphalt mix performance in relation to actual traffic demands and environmental variations (temperature, humidity, aging).

2. **Study the influence of bitumen type (plain and polymer-modified)** on the mechanical and thermal behavior of asphalt mixtures, with the application of state-of-the-art testing methods (TSRST, UTST, TCT, RT, UCTST).

3. **Evaluation of the performance of asphalt mixtures at low temperatures** using rheological and structural methods (BBR, DSR, Fraass, TSRST) to determine the critical cracking temperature and the behavior under thermal shrinkage restraint.

4. **Investigation of the effect of accelerated ageing on bituminous binders and mixtures** by applying the RTFOT procedure, with evaluation of the impact on stiffness and cracking temperature parameters.

5. **To establish correlations between the physical-mechanical properties and performance of asphalt mixtures** in order to formulate predictive models of road behavior based on laboratory results.

6. **Formulate concrete technical proposals for updating the performance requirements in the AND 605 standard**, in particular the introduction of the TSRST breaking temperature as a parameter for mix selection according to the technical class of the road.

The work is structured in seven major chapters, grouped in two distinct parts - a documentary synthesis that theoretically and normatively substantiates the research topic and an experimental study that validates the hypotheses formulated in an applied way.

- **Chapter 1 - Introduction. The necessity and timeliness of the topic**: outlines the current context of asphalt research, the relevance of the topic to modern road infrastructure and the rationale for the chosen research direction.

Part I: Documentary summary

- **Chapter 2** introduces the concept of performance in the context of asphalt mixes and defines the key characteristics (materials, compaction, environmental and loading conditions).
- **Chapter 3** further analyzes the constituents of asphalt mix, with emphasis on the influence of aggregates, filer, bitumen and modifiers on asphalt mix performance.
- **Chapter 4** describes the main physico-mechanical characteristics used in performance evaluation: stiffness modulus, resistance to permanent deformation and low temperature cracking, complemented by specific test methods and the influence of each component.

Part II: Experimental study

- **Chapter 5** presents the laboratory research program, organized in stages of analysis of the performance of the component materials, the influence of the environment and traffic on the behavior of asphalt mixtures, and an applied analysis of compliance with the requirements of AND 605.
- **Chapter 6** details an applied experimental modeling - the case study - for the analysis of low temperature behavior. The influences of bitumen, ageing and environmental conditions are investigated by dynamic testing using methods such as Fraass, BBR TSRST, UTST, RT, TCT and UCTST.
- **Chapter 7** brings together the final conclusions, highlights the original research contributions, the dissemination work and proposes future directions for further research.

The bibliography consulted for the elaboration of the doctoral thesis is presented at the end of the thesis and includes 129 bibliographical references.

2. Description of the concept of performance in the research of asphalt mixtures used on roads

Chapter 2 provides a detailed analysis of the concept of **performance** in the context of asphalt mixtures used in road infrastructure, highlighting both theoretical approaches and the regulatory and practical developments at national and international level.

- **Defining performance and its relevance in road engineering**

Globally, over 90% of asphalt mixtures are used for road construction and rehabilitation. From this perspective, the performance of asphalt mixtures is essential to ensure the durability, sustainability and safety of infrastructure. This is determined by a multitude of factors: material composition, placing conditions, traffic demands and climatic conditions.

Performance is traditionally assessed by physico-mechanical characteristics obtained in the laboratory, but the modern approach requires the simulation of real conditions through accelerated tests, which allow the choice of the optimal recipe. The focus is on the **correlation between material characteristics and in-service behavior**.

- **Determinants of asphalt mix performance**

a) Materials

The basic components - aggregates, filer and bitumen - play critical roles. Aggregates account for up to 96% of the mix and directly influence stability and compactability. Filer helps to strengthen the binder and fill the spaces between aggregates. Bitumen, the main binder, can be plain or modified, depending on strength, durability and thermal behavior requirements.

b) Additives and fibers

To improve performance, additives and fibers (cellulose, polyester, minerals) are used to increase fatigue, crack and wear resistance, thus increasing the durability and efficiency of the mixes.

c) Compaction

Compaction directly influences the performance, density and impermeability of the mix. It is affected by aggregate characteristics, viscosity of bitumen, temperature during placing and layer thickness. Various laboratory methods are used to simulate field conditions (gyratory compaction, impact compaction, etc.).

d) Environmental conditions

Temperature and humidity influence the viscosity of the binder and the general behavior of the mix. At high temperatures stiffness decreases, the risk of plastic deformation (rutting) increases, and at low temperatures the risk of cracking increases. The studies cited show a significant decrease in stiffness with increasing temperature.

e) Loading conditions

Road traffic, especially heavy traffic, contributes to deformation and cracking. The rate of degradation is influenced by the frequency and intensity of loading. Vehicle speed, contact pressure and temperature have been found to have a major impact on structural performance.

- **Performance assessment - research and regulation**

Modern evaluation of mixes is based on performance indicators: crack resistance, stiffness, rutting resistance, etc. Internationally, standards such as JTG H20-2007 (China) and recent research propose evaluation models that correlate production data with in-service performance.

CAM modeling, electron microscopy, automated photogrammetry systems and WIM sensors are modern tools that provide a detailed insight into the behavior of mixtures.

- **Technical regulations in Romania**

In Romania, the evaluation of asphalt asphalt mixtures is regulated by the **AND 605 standard** and the **SR EN 13108 series of standards**, which establish the technical conditions for the component materials, test methods and acceptance criteria. Detailed tables are provided for aggregates, filer, bitumen and the final mix, including relevant dynamic tests (stiffness modulus, creep resistance, fatigue, etc.).

The types of mixtures used are categorized by layer (wearing, binder, base) and are constantly being updated, with the last update of the standard in 2023. Rec reclaimed asphalt bituminous asphalt asphalt has been introduced and rough asphalt asphalt concrete has been eliminated, indicating a trend towards optimizing the composition based on performance.

- **Conclusions and comparative summary**

Asphalt performance is a complex function of several interdependent parameters: materials, composition, compaction method, environmental conditions and mechanical stresses. The evolution of standards (national and European) reflects this complexity, moving from empirical requirements to performance-based specifications.

The current trend is to use recipes optimized by laboratory testing, integrated with advanced simulations of behavior under real conditions. The aim is to develop asphalt mixtures that are stronger, more durable and more sustainable, adapted to Romanian conditions but compatible with international requirements.

3. Analysis of asphalt mix constituents to determine the performance level

Chapter 3 investigates, on experimental and bibliographical bases, the influence of each constituent (aggregates, filer, binder, modifiers) on the performance of asphalt mix designed in the laboratory. The aim is to substantiate the selection and dosage criteria of the materials so that the chosen recipe meets the strength, durability and sustainability requirements imposed by European standards and Romanian road conditions.

- **Building performance - overview**

Asphalt performance results from the interaction of the triad:

1. Aggregate - forms the strength skeleton;
2. Binder (bitumen) - provides cohesion and water resistance;
3. Bitumen-aggregate interface - determines water sensitivity and fatigue resistance.

Key parameters measurable in the laboratory are established for each component and then correlated with the dominant types of degradation (rutting, thermal cracking, fatigue).

- **Aggregates - the mechanical skeleton**

- The grain size composition is evaluated by sieving; the shape of the curve (log. d-% passing) controls the compactability and volume-volume-goals.
- The coefficient of non-uniformity (Un = d60/d10) is used to quantify the grain distribution; an optimum Un avoids segregation and ensures high density.
- Shape and texture: polyhedral particles impart high internal friction angle; lamellar/acicular granules are undesirable-cause cracking under traffic.
- Fragmentation resistance (LA, micro-Deval) indicates durability under wear and impact.
- The volume of voids simultaneously influences impermeability, freeze-thaw resistance, fatigue sensitivity and permanent deformation.

- The cleanliness of the aggregate (impurity content < limits SR EN 933) is essential for adhesion.

Conclusion: Aggregates should be selected to provide continuous skeleton, good interlock and wear resistance, while maintaining a void volume compatible with the amount of binder available.

Filler

- Dual role: (i) completes the particle size curve by filling the micro-goles; (ii) reacts with bitumen to form mastic.
- Critical influences: the fineness, mineralogy and chemical reactivity (pH) affect the viscosity of the filler, temperature susceptibility and moisture resistance.
- Filler/bitumen ratio - functional threshold: at ratio < 1 viscosity increases moderately; above 1 a maximum density system (Rigden) is formed which stiffens the mixture.
- Research shows that hydrated lime filer stiffens most effectively, but also improves resistance to thermal cracking; very fine fillets increase bitumen requirements.
- The use of alternative fillers (fly ash, marble dust, granulated slag) can reduce costs and CO_2 footprint, provided granulometric and chemical control.

Conclusion: Optimization of the content and type of filler is decisive for the stiffness-durability balance of the mixture.

Bitumen - viscoelastic binder

Fundamental properties

- Penetration, softening point, IP: describe the consistency and thermal susceptibility; IP values between -1 and +0.7 give balanced performance.
- Fraass point indicates the cold cracking temperature limit.
- Ductility reflects tensile deformation capacity - critical in cold areas and at joints.

Reology

- Bitumen is a viscoelastic material: instantaneous elastic response + delayed elastic response + viscous component (creep curve).
- SOL / GEL / SOL-GEL colloidal structures (SARA ratio) determine the flow mode; asphaltene content increases viscosity and reduces thermal susceptibility.

Modifiers and add-ons

- SBS polymers (the most widespread family) increase elasticity and rutting resistance; the optimum dosage depends on the penetration of the base bitumen.

- Fibers (cellulose, polyester, basalt) provide three-dimensional reinforcement, improving fatigue and cold cracking.
- Agents to improve adhesion > 80% to hydrophilic aggregates.
- Targeted effects: controlled hot stiffening, cold elasticization, extended service life without penalizing workability.

Evaluation procedures (pre-2015 → post-2015)

- The transition from SR 174 (empirical) to AND 605 + SR EN 13108 introduced complex tests (Stiffness, Dynamic Creep, TSRST, BBR) to simulate real conditions (traffic, temperature, humidity).
- The binder is characterized in parallel on the fresh → RTFOT → PAV route to estimate the aging sensitivity.
- Correlation of laboratory results with 1:1 pilot sectors validates the prediction models.

Summary and implications for optimal recipe design

1. Aggregates: choice based on shape, cleanliness and strength, ensuring a void volume compatible with the binder content.
2. Filer: dosing so that the filer/bitumen ratio maximizes the density of the mastic without inducing brittleness.
3. Bitumen: selected by penetration index and modifiers for the targeted climate and traffic.
4. Performance testing: application of the full set of dynamic and thermal tests for calibration; results are integrated into fatigue life and permanent deformation models.

Expected result: obtaining a balanced mix - stiff when hot, flexible when cold, resistant to moisture and ageing - capable of meeting European standards and prolonging the service life of Romanian roads.

4. Physico-mechanical characteristics used to evaluate the performance of asphalt asphalt mix for roads

Modulus of elasticity, modulus of rigidity and complex modulus

The evaluation of asphalt mixtures is based on modulus of elasticity, modulus of stiffness and complex modulus. The modulus of elasticity (E), or Young's modulus, is a constant expressing the ratio between the applied stress and the resulting strain in an elastic material. The formula developed by L. Francken emphasizes that this modulus depends on the proportions of aggregates, bitumen and voids in the mix.

The modulus of stiffness expresses the behavior of mixtures under mechanical stresses, depending on factors such as mixture composition, degree of compaction, temperature and load frequency. Tests show that stiffness decreases with increasing temperature and that higher compaction increases stiffness.

The complex modulus (E*) describes the viscoelastic behavior of the mixtures and includes an elastic (E') and a viscous (E''') component. Graphical representations by Black and Cole-Cole diagrams allow a detailed understanding of the relationship between these components and temperature and traffic conditions.

- **Assessment of permanent deformation of asphalt mixtures**

Permanent deformation is a consequence of the viscoelastic and plastic behavior of asphalt mixtures. They occur in the form of wheel rutting caused by heavy traffic, high temperatures, insufficient compaction or unsuitable mix designs.

There are three types of deformation:

- Wear - determined by tire texture and wear layer;
- Creepage - the result of stresses above the limit of structural stability;
- Structural deformation - resulting from undersized road structure.

The relevant laboratory tests are:

- Cyclic compression test (dynamic creep) - assesses the deformation accumulated over time;
- Wheel tracking - measures track depth under repeated loads.

Key factors in preventing rutting are: optimum binder content, void volume (ideally ≈ 3%), nature and shape of aggregates. Angular, rough-textured aggregates increase interlock and deformation resistance.

- **Resistance to fatigue cracking and low temperatures**

Fati fatigue cracking occurs under moderate temperature cycling loads. It is influenced by bitumen content and type, void volume, aggregate type and compaction methods. A mix with more bitumen and a low void volume has a higher resistance to cracking due to uniform stress distribution.

Laboratory tests used include:

- Two, three and four point bending attempts;
- SCB testing for crack propagation;

- IDT tests for indirect stretching.

Low temperature resistance is essential in preventing thermal cracking. This is tested by methods such as UTST, TSRST, TCT, RT and UCTST. The binder plays an essential role, with soft bitumens and polymer modifiers improving the performance of the mix.

Thermal cracking can also be direct (below -30°C) or by thermal fatigue. It is influenced by the stiffness and relaxation of the binder, the coefficient of thermal expansion and the interaction with the aggregates. Angular shaped aggregates with a rough surface provide better adhesion and reduce the risk of cracking.

5. Laboratory research program: performance evaluation of asphalt mixtures

The research program was conceived in accordance with the Romanian AND 605-2016 and the European SR EN 13108-5 standards, focusing on the evaluation of asphalt mixtures behavior in relation to the real traffic demands and the specific climatic conditions in Romania. The experimental work was carried out in a RENAR accredited laboratory and included physico-mechanical and rheological tests on test specimens using modern equipment.

- **Materials used**

Asphalt mixtures produced with two types of bitumen were analyzed:

- Bitumen 50/70 (plain)
- Polymer modified bitumen (PMB 45/80-55)

Each mix type was tested both fresh and after accelerated aging according to the RTFOT method. The materials included crushed natural aggregates and mineral filer according to the technical requirements.

- **Stages of experimental research**

Stage I - Evaluation of the characteristics of the component materials:

- Determination of the granularity and shape of aggregates
- Analysis of binder properties (penetration, softening point, elasticity)

Stage II - Evaluation of the behavior of fresh mixtures:

- Testing the degree of compaction

- Determination of stiffness and resistance to permanent deformation by testing:
    - stiffness
    - rutting
    - creep

Stage III - Environmental and traffic influence assessment:

- Simulate traffic and temperature variations (0 °C, -10 °C, -20 °C)
- Low temperature crack tests: TSRST, Fraass, BBR

- **Test methods used**

Advanced methods:

- TSRST (Thermal Stress Restrained Restrained Specimen Test) - to determine the cracking temperature
- BBR (Bending Beam Rheometer) - measures stress relaxation in the binder at low temperatures
- DSR (Dynamic Shear Rheometer) - analyzes rheological behavior at high temperatures
- UTST and UCTST - uniaxial tensile tests for strength and deformability analysis

Traditional methods:

- Marshall tests - to assess mix stability and creep
- RTFOT ageing tests - to reproduce changes due to oxidation processes

- **Results and interpretations**

The results revealed that:

- **Modified bitumen (PMB)** gives mixes increased stiffness and greater resistance to deformation and cracking, especially at low temperatures;
- RTFOT **aging** significantly reduces stress relaxation capacity, increasing the risk of thermal cracking;
- **Rutting performance** is better with modified bituminous mixtures, as they have a shallower rut depth after repeated stress cycles;

- There were clear correlations between **physical-mechanical properties** and **critical cracking temperature**, which validates the applicability of TSRST and BBR tests in performance-based design.

Interim conclusions

The experimental work in Chapter 5 validated:

- Need to use advanced testing for asphalt mix design;
- The importance of adapting recipes to local climatic conditions;
- The efficiency of modified bitumen for high-stress roads;
- The possibility of including the "TSRST breaking temperature" parameter in the AND 605 standard as a technical selection criterion for mixtures.

6. Applied experimental modeling: low temperature behavior analysis

The research aimed at investigating the behavior of asphalt mixtures at low temperatures, using a complex and multidimensional approach integrating advanced testing methods. The main aim was to determine the thermal and mechanical performance of the mixes, in particular their ability to resist cracking under severe climatic conditions.

Objectives and methodology

The objectives of the study were:

- Assessment of resistance to cracking at negative temperatures;
- Determination of stiffness and relaxation capacity of internal stresses;
- Performance comparison of standard and modified bitumen mixes;
- Investigating the influence of accelerated aging on cold behavior.

Two types of mixtures were analyzed: one with bitumen 50/70 and one with modified bitumen PMB 45/80-55. The tests were performed on both unaged and RTFOT aged specimens.

Test methods used

TSRST (Thermal Stress Restrained Specimen Test)
The test simulated restricted thermal shrinkage of the mixture. It allowed the measurement of the rupture temperature and internal stresses generated by controlled cooling. The specimens were cooled from 20°C to -30°C at a rate of 10°C/h. The critical cracking temperature (Tcr) and the maximum stress value were determined.

Fraass - the brittle point of bitumen
Classical method that determines the minimum temperature at which the binder remains flexible.

BBR (Bending Beam Rheometer)
Measured the relaxation capacity of the bond at -12°C, -18°C and -24°C. Key parameters: modulus of stiffness (S) and relaxation rate (m).

DSR (Dynamic Shear Rheometer)
Provided information on the rheological behavior of bitumen, in particular its ability to resist viscoelastic cracking.

UTST (uniaxial tension stress test)
Evaluated the strength of the mix under axial tension at low temperatures, showing the influence of ageing on the strength.

- **Results and interpretations**

TSRST
The modified bitumen mixes exhibited a significantly lower critical cracking temperature (≈ -23.5°C) compared to plain bitumen (≈ -17.5°C), indicating better cold flexibility. The maximum stress at cracking was higher for PMB, confirming a better resistance capacity.

Fraass
Modified bitumen had a lower embrittlement point (≈ -24°C), whereas 50/70 bitumen cracked at ≈ -17°C.

BBR
Results indicated that PMB binder met the performance criteria for all three temperatures analyzed, while 50/70 bitumen exceeded the limits at -24°C. After ageing, both binders lost some of their ability to relax, but PMB retained better performance.

DSR
The modified bitumen showed a more balanced viscoelastic behavior, with a phase angle closer to the ideal behavior for heavy-duty roads.

UTST
PMB mixes exhibited increased axial tensile strength, maintaining their structural integrity even after aging. Those with standard bitumen showed a sharp decrease in performance.

- **Comparative analysis and interim conclusions**

  - **PMB-modified bituminous** mixes have demonstrated superior performance at low temperatures, both in terms of **flexibility** and **mechanical strength**.

- **Accelerated aging** has a significant impact on cold behavior, but PMB better compensates for these effects.
- The introduction of **TSRST** as a standard method in AND 605 is justified, due to its relevance in simulating real road behavior.

Original contributions and practical implications

- The thesis proposes an integrated, multidisciplinary testing framework adapted to Romanian climatic conditions;
- Provides **factual data** to inform the update of AND 605;
- It also recommends **classifying asphalt mixtures** according to critical cracking temperature, not just creep and rutting.

7. Final conclusions, original contributions, dissemination of information and future research directions

General research findings

The thesis aimed to evaluate the performance of asphalt mixtures through a complex approach, centered on the determination of a performance index that allows the selection of the optimal recipes in the laboratory design phase. The main aim was to correlate the physical-mechanical characteristics with the in-service behavior of asphalt mixtures.

The literature review identified the main degradation mechanisms of road surfacings (rutting, fatigue cracking and low temperature cracking) and the experimental study tested 5 bitumen types from two sources and two aggregate types with and without polymer additions.

Relevant results from experimental tests

- **The stiffness modulus** is influenced by the consistency of the bitumen and the frequency of stress: it is higher at short stresses and low temperatures.
- Polymer-modified bitumens offer lower initial stiffness but **higher viscosity**, superior Marshall stability and **better performance at negative temperatures**.
- **Y-source aggregates**, although less wear resistant, led to increased stiffness of the mixes.
- **Permanent deformations** are lower at low temperatures (40 °C vs 50 °C - difference of about 27%).

- **Bitumen 70/100 or PMB bitumen** mixes were resistant to cracking down to -33 °C...-37 °C, compared to -25 °C...-26 °C for bitumen 50/70.

Proposals to update AND 605

- Introducing the **TSRST** test and the minimum cracking temperature (Trupere) as **selection criteria** for asphalt mixtures.
- For class I/II roads: Temperature ≥ -25 °C
- For class III/IV roads: Temperature ≥ -20 °C
- Review the test methods, reference temperatures and ageing conditions required in DNA 605.

Original scientific contributions

- **Calculation of performance indices** for each physical-mechanical characteristic, integrated in a multi-criteria evaluation system.
- **Advanced and comparative use** in Romania of the TSRST, UTST, TCT, RT and UCTST tests for the evaluation of asphalt mixtures.
- **Rheological correlation between bitumen and mix**: direct links between DSR/BBR parameters and TSRST behavior, with a statistically validated predictive model ($R^2 = 0.84$).
- **Formulate a concrete proposal** for the revision of AND 605 on cold temperature behavior.
- **Implementation of TSRST equipment** and development of standardized test procedures within CESTRIN.

Disseminating results

Results were disseminated through conference presentations and journal articles. The most relevant include participation in:

- CETRA 2018, Zadar, Croatia;
- National Roads and Bridges Congress, Iași;
- "Roads - Bridges" magazine;
- UTCB Doctoral School Conferences.

Future research directions

1. **Assessment of long-term aging (PAV)** for correlation with field behavior;
2. **Tests on experimental road sections** for validation under real conditions;
3. **Study of sustainable blends** with recycled polymers or environmentally friendly additives;
4. **Combined temperature-humidity analysis**, relevant for continental climate;
5. **Alternative accelerated ageing methods** closer to reality;
6. **Integrating laboratory parameters into road dimensioning**;
7. **Complete revision of AND 605** in line with European practice and recent research results.