

UNDERSTANDING ASPHALT COMPACTION: AN ACTION RESEARCH STRATEGY

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ABSTRACT: In Hot Mix Asphalt (HMA) construction, rollers provide the compaction energy required to produce a specified density. However, little is known about the heuristics used by the roller operators. This study forms part of a larger action research project focussing on the improvement of the HMA paving process. The aim is to develop a deeper understanding of the relationship between and the effect of operator heuristics, motion patterns, coverage patterns, temperature differentials and other characteristics during the compaction process. We describe the importance of the compaction process; discuss the role of the compactor operator; present developments in the use of Global Positioning Systems to assist the compaction process; and briefly discuss technology adoption in the context of the construction industry. Lastly, we propose an action research methodology involving the researcher, innovative technologies and most importantly, operators involved in the compaction process. This is expected to lead to improved control during the compaction process and consequently improved product and process performance.

Keywords: asphalt, compaction, GPS, operator, process

1. INTRODUCTION

Over the last three years, since the parliamentary enquiry into the construction sector, the business environment within the road construction sector has changed dramatically in the Netherlands. According to (Dorée, 2004) the collusion structure that regulated competition has fallen apart. Public clients have introduced new contracting schemes containing incentives for better quality of work (Sijpersma and Buur, 2005). These new types of contracts, tougher competition and the urge to make a distinction in the market, spur the companies to advance in product and process improvement. These changes have significantly altered the playing field for competition. The companies see themselves confronted with different “rules of the game” than what they were used to. Performance contracting and longer extended guarantee

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period create a new set of risks and business incentives. In general, the companies experience the pressure of the new types of competition, but at the same time they do acknowledge the opportunity to distinguish themselves.

Asphalt paving companies face a new setting to perform and compete. In an effort to outperform competitors, they seek better control over the paving process, over the planning and scheduling of resources and work, and over performance. Improved control would also reduce the risks of failure of the paving during the guarantee period. To be able to achieve these goals, the relevant operational parameters need to be known and the relationship between these parameters needs to be thoroughly understood. For the asphalt paving companies to be able to improve product and process performance, they now more than ever acknowledge they need to develop intricate understanding of the asphalt paving process and the interdependencies within.

2. RESEARCH OBJECTIVES

This study forms part of a larger action research project focussing on the improvement of the Hot Mix Asphalt paving process with a view to improving product and process performance. The objectives of the overall project are: (a) to develop tools for analysis of the asphalt paving process, (b) to build process models of the asphalt paving process, and (c) to bring these models together in an event scheduling simulation system.

The aim of this part of the project is to develop a deeper understanding of the compaction process since compaction is probably the most crucial stage in the operator's construction of any layer within a road pavement (Shell, 1990). Consistent and controlled compaction processes will contribute to consistency and quality of the paving. This entails developing an understanding of the relationship between the compaction grade, motion patterns, coverage patterns, temperature differentials and other characteristics during the compaction process. Since the operators cope with these factors on day to day basis, it seems highly valuable to start with mapping the heuristics the operators use, and unravelling the logic and tacit knowledge about the do's and don'ts in the compaction process (from the operators' perspective).

3. IMPACT OF COMPACTION ON THE QUALITY OF THE ROAD PAVEMENT

A decisive factor in ensuring satisfactory pavement performance is the final density of the pavement after compaction. Hughes as cited in (Li et al., 1996) defines compaction as "... the process of reducing the air voids content of asphalt pavement between the solid particles. It involves the packing and orientation of the solid particles into a more dense and effective packing arrangement". The goal of compacting an asphalt pavement is to achieve an optimum air void content, to provide a smooth riding surface and to increase the load-bearing capacity of the material under construction (Asphalt-Institute, 1989).

Most contract specifications stipulate either a specific percentage of voids or a final density that needs to be achieved by contractors (NCAT, 1991). For achieving the required final density, the asphalt layer must be uniformly compacted by means of a specified number of compactor passes. A high compaction level will result in stable particle stacking, a significant number of inter-particle contact points and a low void content. However, caution is needed. Outside of the laboratory, reaching the required level of compaction proves to be quite a complex matter. Under-compacting will leave to many voids, stiffens and reduces stability and strength of the pavement. Over-compaction creates the danger of flushing and the mixture becoming unstable. This (ter Huerne, 2004) points out, is due to the effects of thermal expansion of the different mix components.

The impact of operational decisions on the ultimate compaction level is show by (Krishnamurthy et al., 1998). Their research showed that the compaction was not uniform. When looking at cross section of the roads, the density in the centre of the road was consistently higher than the density at the edges. This effect was due to the operational choices of the operators. The authors suggest that operators where prone to create more overlap in the centre of the road. This overlapping – deliberate or not - can cause over-compaction and under-compaction in various areas of the pavement and so result in non-uniform compaction. In general joints and edges are two areas in a pavement that consistently receive less compaction than the rest of the cross-section. This is illustrated in Figure 1 which shows typical distributions of compactor passes and the resulting compaction obtained during trials undertaken by the Transportation and Road Research Laboratory in the United Kingdom (Leech and Selves, 1976).

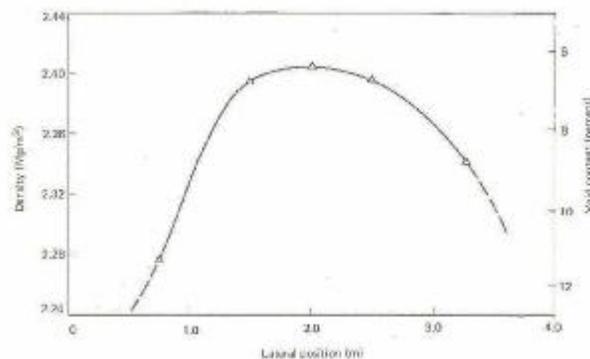


Figure 1 - Distribution of densities and compactor passes across the laid width for Dense Bitumen Macadam (Source - TRRL, 1976)

The number of passes is not the only factor to consider for compaction. Other factors also come into play. These include subgrade support, working temperature, material properties, outside temperature, layer thickness, aggregate grading and the mix design. Compaction is also affected by construction equipment and variables such as compactor speed, compactor frequency, amplitude, wheel load and importantly, the number of passes performed by the compactor operator (NCAT, 1991). These complex set of factors provides the operators with as (Schon, 1983) states, a "mess" or as (Conklin and Weil, 1999) say, a "wicked" problem. Given the circumstances the asphalt compactor operators have come up with an operational strategy in order to compact the asphalt to the desired density. During the compaction the operators

have to make deliberate operational decisions about timing, speed, trajectory and whether or not to vibrate. For that the operators have to build and maintain complex mental maps of each site, the circumstances, the compaction sequence, the progress made, and also be aware of their colleagues' operations. Moreover, the difficulty of performing this complex compaction task under frequently changing site conditions is illustrated by the research of (Bouvet et al., 2001), who report that compaction errors induce frequent defects in the final pavement structure. These errors are due to restricted human capacity and bounded rationality. The complexity of operators' tasks may affect the quality, the productivity and the project cost negatively.

Consequently, the understanding of the compactors operations and an analysis of the subsequent intuitive reasoning for aspects thereof is urgently needed in order to improve the asphalt compaction process. Explicit process knowledge may provide support for and a deeper understanding of the process being followed. Improving the control over compaction processes is an essential step towards improving the control over pavement quality. The first step towards insight into compaction and operational strategies is documentation of the operations on site. Logging the movements of the equipment captures the results of the operational choices made by the operators. The documented operations will also provide the lever to discuss the operational choices with the operators. The logging and documentation of site operations will, in this research project, be achieved by tracking the movements of the compactors using GPS technology.

4. DEVELOPMENTS IN THE USE OF GLOBAL POSITIONING SYSTEMS (GPS) TO ASSIST THE COMPACTION PROCESS

To monitor the coverage of the compaction compactor, its precise location needs to be known at all times. This can be done using global positioning systems (GPS). The GPS receiver is a passive device that receives signals from orbiting satellites. The receiver is able to triangulate its two-dimensional position and altitude anywhere on the surface of the earth using a minimum of three satellites.

GPS technology has become quite common since the introduction of satellite-navigation systems in automobiles. Before GPS became so mainstream, there have been several organized industry-aided research efforts for the development of state-of-the-art technologies for real-time locating and positioning systems for construction operations (Abourizk and Shi, 1994; Pampagnin et al., 1998; Bouvet et al., 2001; Hildreth, 2003). Some of these include efforts to develop automated methods for monitoring asphalt laying and compaction using GPS and other IT technologies.

(Li et al., 1996) reported on a system to map moving compaction equipment, transform the result into geometrical representations, and investigated the use of Geographic Information System (GIS) technology to develop a graphical illustration depicting the number of compactor passes. The system uses automated real-time positioning through the use of differential GPS which can have an accuracy of better than 100mm. A positioning device placed on the compactor records positioning information and uses wireless technology to transmit the information to a remote computer. Software written using Microsoft Visual Basic™ derives a graphi-

cal depiction of the number of passes executed over the length of the roadway using a GIS overlay technique.

(Peyret, 1998) defined positioning systems in the context of road construction sites and emphasizes the advantages offered by the new generation of systems, making specific reference to the use of GPS. The system is made up of a fixed station reference receiver and a mobile receiver (rover) linked to a microprocessor to perform real-time processing. The major drawbacks of GPS application in the field of road construction equipment positioning are highlighted, namely the accuracy limits, the initialization time after blind periods that increase the gaps in positioning and the fragility of the real-time radio link.

(Krishnamurthy et al., 1998) developed an Automated Paving System (AUTOPAVE) for asphalt paving compaction operations. The system was developed using GPS technologies and included developing a semi-automated path-planning and real-time guidance system to automate the paving operation. The system accepts relevant paving project inputs, generates path plans, presents a graphical visualisation of the generated path plan and offers real time guidance capabilities. The system offers an interactive, user-friendly, graphical interface with real-time tracking and path guidance features, incorporating visual and audio guidance capabilities.

(Peyret et al., 2000) reported on their Computer Integrated Road Construction (CIRC) project. This aims to develop Computer Integrated Construction systems for the real-time control and monitoring of work performed by road construction equipment, namely compactors (CIRCOM) and pavers (CIRPAV). It is based on a methodology of sharing common numerical geometric data from design, through all site operations up to the quality control of the geometry of the structure. It relies on CAD software tools, automatic control, short-range wireless data communication and real-time positioning. The main objective of CIRCOM is to assist the compactor operator, so that he can perform exactly the required number of passes, at the right speed, everywhere on the surface to be compacted. A second objective is to record the actual work achieved in the trajectory followed and the number of passes achieved on every point of the trajectory, in order to feed the site database and to perform global quality control at the site level.

(Oloufa, 2002) described the development of a GPS-based automated quality control system for tracking pavement compaction. The research team proposed using a system consisting of positioning devices, hardware and software, and experimented with vector and raster-based algorithms to develop a Compaction Tracking System (CTS). The design allows multiple compactors to be tracked since the main processing tasks are done at the base station. A graphical depiction shows the number of passes executed over a length of roadway. The architecture also allows the simultaneous creation of an independent record of the compaction process.

Overall, we can conclude that the idea of using GPS and other technologies in asphalt paving processes is not a step in the dark. Several experiments have been conducted in recent years. However, although some of these experiments were developed into industrial applications, it appears that few have been accepted widely by industry and are frequently used on the construction sites. Although some equipment manufacturers now provide GPS as an option for clients, GPS is not yet part of operational strategies and working practice in compac-

tion processes. So, although GPS technology has been subject of study in paving processes, and is now available on roller equipment, it is not yet adopted and integrated in operational strategies and methods. Key in this slow adoption seems the (insufficient) accuracy of the stand alone GPS receivers.

5. TECHNOLOGY ADOPTION IN CONSTRUCTION

In the Netherlands, experts and representatives of agencies in the field of asphalt technology confirmed that (a) the asphalt paving process depends heavily on craftsmanship; (b) the work is generally carried out without the instruments to monitor the key process parameters (temperature, compaction and layer thickness); and (c) the work methods and equipment are selected based on tradition and custom (Dorée and ter Huerne, 2005). For his MSc thesis (Simons, 2006) interviewed 28 compactor-, paving- and screed operators actively involved in the asphalt paving process. The interview results confirmed that the compaction process to a large extent depends on tradition and custom i.e. the knowledge and experience of the compaction team. Machine settings are mainly done on the basis of “feeling and experience”. Compactor operators visually note the behaviour of the mix to determine if the desired density has been achieved. Although the interviewees all refer to common and proven practice in machine setting, the actual settings and operational strategies varied widely from team to team. So there is not really one common practice, but wide array of “common practices”. A worrying feature is that most operators acknowledged that they hardly made use of the technology available on the compactor or even simple temperature measurement instruments to assist them in the compaction process. (Quist, 2006) also highlighted this apparent mismatch between technology and the operators.

Several authors argue that the construction industry typically lags behind other industries in adopting technology ((AbouRizk et al., 1992; Halpin and Martinez, 1999). (Halpin and Kueckmann, 2002) are rather critical of the construction industry and the slow progress in adopting technology to assist construction processes. They suggest that construction lacks the “culture of change” which drives other industries and that “Construction has for 5 thousand years visualised an end item and then generated methods or processes to achieve the end item. These processes have remained static and produced facilities which don’t fully meet the needs of the user but are accepted since the means, materials and methods of building are entrenched”. However, (Bowden et al., 2006) raises an interesting perspective and suggests that progress to modernise the construction industry has been driven by a combination of “technology push and demand pull” and that that many would argue that the reason the construction industry has been slow to adopt new technologies is that they have not yet been fully developed to suit the needs of the industry, hence there is a strong demand pull which is yet to be satisfied. The prime problem seems to be that previous experiments represented too much of a technology push with little involvement of those destined to use the technology. In discussing strategies for technology push, (Betts and Ofori, 1994) believe that studies on technology adoption should consider both the “hard” issues of techniques and materials and the “soft” human side.

(Simons, 2006) suggests that the adoption process may be hindered by scepticism and reluctance of the operators who feel that their workmanship is being devalued or that management could use the technology to track their movements and possibly use it punitively. For adoption of technology in construction, factors as given by (Rogers, 2003) have to be taken into account, and operators have to be participants in the development process (the technology must support them and not the other way around). That corroborates with the findings of the equipment manufacturers and the actual conduct of the operators as interviewed for this project.

Five innovation adoption attributes explain significant variance (Rogers 2003):

- Ø Relative advantage
- Ø Compatibility
- Ø Complexity
- Ø Trialability
- Ø Observability

6. ACTION RESEARCH STRATEGY

Based on the above, the situation can be summarised in the following statements:

- The Dutch highway agencies altered their public procurements strategies towards performance contracting and longer guarantee periods, and as such create new competitive environment for the paving companies;
- The asphalt paving companies acknowledge they have to make an effort to improve product and process performance, and therefore they now need more intricate understanding of the asphalt paving process and the interdependencies within;
- Up till now the companies lean heavily on the experience and tacit knowledge of the construction teams on site. Investigation into operational strategies and process control requires objective documentation of the processes on site. GPS technology offers opportunities for logging equipment movement; and
- Several experiments have been conducted in recent years using GPS and other new technologies to improve the compaction process. Although these experiments were developed towards industrial applications, evidence suggests that the industry has not adopted these new tools.

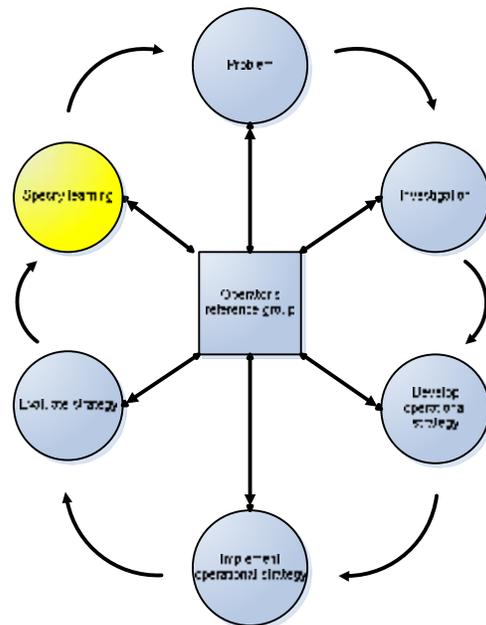


Figure 2 - Action research strategy for the asphalt paving process

Given the ambition to improve the product quality and process control consistently the companies need to widen and deepen understanding of the operational strategies for paving and compaction processes:

- To widen and deepen understanding of the operational strategies for paving and compaction process they need to adopt new technology (as GPS);
- Adoption of new technology (as GPS) seems to fail because the tools are not tailored to the mental frame and operational strategy of the people involved.

So, developing improved operational strategies requires adoption of new technologies, but new technologies are not adopted due to insufficient understanding of current operational strategies (the common practice). This resembles a chicken or egg problem, a causality dilemma. Against that back ground the research project follows an action research strategy alternating steps of technology introduction and mapping of operational strategies (see Figure 2). Through monitoring of the learning processes of the operators, and evaluating the operational choices with them, the tacit knowledge of the "common practice" will become explicit. As such this provides the opening for further development of process understanding, tools and operational strategies. Qualitative heuristics will be confronted with quantitative process data.

This simply means that it firstly, involves the compactor operators directly in the research project and secondly, it includes a statistical modelling and computer simulation component that aims to test and validate models developed during the research. The explicit models will facilitate the practitioners in synthesizing their tacit knowledge and promote learning processes. (Trochim, 2001) suggests that "there is so much value in mixing quantitative and qualitative research. Quantitative research excels at summarising large amounts of data and reaching generalisations based on statistical projections. Qualitative research excels at telling the story from the participants viewpoint, providing the rich descriptive detail that sets quantitative results into their human context".

The aim is for operators and researchers to jointly develop operational strategies using an iterative process (see Figures 3 and 4) of problem definition, operational strategy development, implementation, evaluation, and consciously specifying the learning taking place. This is expected to lead to:

- Better understanding of the compaction process;
- The development of innovative tools and technologies to assist understanding of the compaction process; and
- Adoption and wider acceptance of innovative tools and technologies and its associated benefits.

Figure 3 - Iteration process

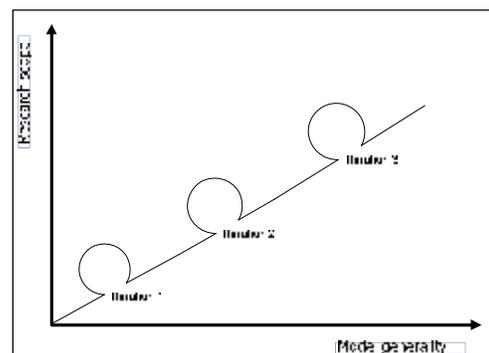
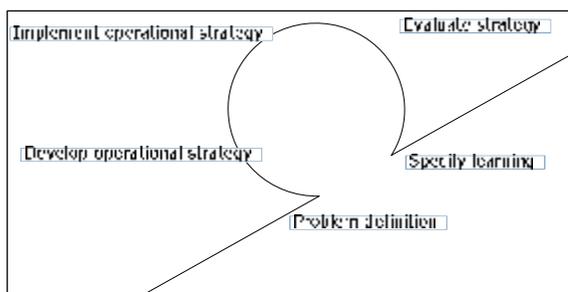


Figure 4 - typical iteration

A qualitative paradigm should provide insight and understanding from the perspective of those actually involved in the asphalt construction process. One of the major distinguishing characteristics of qualitative research is that the researcher attempts to understand people in terms of the own definition of their world (Mouton, 2001). By utilising a qualitative approach, an attempt will be made to understand the asphalt construction process, from the subjective perspective of the individuals involved. These individuals include the operators involved in the actual paving process. The complexities can only be captured by describing what really goes on in their lives, incorporating the context in which they operate, as well as their frame of reference. In other words, there needs to be a commitment to the empowerment of participants and the transfer of knowledge. (Chisholm and Elden, 1993) advises that one should strive for the full involvement of the client (in this case the compactor operators) and researcher. The involvement of participants enhances the chances of high construct validity, low refusal rates and “ownership” of findings. The validity should also benefit by several iterations and expansion of the research scope across iterations. This is illustrated in Figures 3.

A qualitative approach therefore has the potential to supplement and reorient our current understanding of the asphalt paving process. Key research questions using an action research strategy are normally of an exploratory and descriptive nature. Exploratory in that you are attempting to firstly, assess what is happening during the asphalt compaction process and secondly, to identify the key factors that affect the process. Descriptive questions also provide opportunities for finding correlations between variables affecting the paving process.

The quantitative paradigm is aimed at developing and validating accurate models of the somewhat complex compaction process. The overall objective is to build process models of the asphalt paving process and to bring these models together in an event scheduling system. The models to be developed need to be checked and validated in practice. This requires the involvement of stakeholders closest to the asphalt construction process. Several causal and predictive questions have to be addressed during this modelling phase. What are the main causes of variability in the paving process? Is variability the main cause of reduced quality, productivity and efficiency within the paving process? What will the effect of a revised operational strategy be on the compaction process? Will a revised operational strategy lead to improved quality, productivity and efficiency?

With this action research strategy the chicken-or-egg problem (the causality dilemma of technology development and adoption) is side-stepped by progressing in small steps involving the practitioners. The described action research strategy has an additional bonus. Since progress in the research project coincides with actual learning and growth of operational knowledge and capabilities, the companies are happy to take part in the research - instead of just being the object of study. It breaches the classical divide between science and practice. It not only challenges the practitioners' presumption of the paving process, but also their opinions of the value of academics.

7. CONCLUSIONS

A parliamentary inquiry into collusion in the Dutch construction industry sparked new public procurement strategies and altered the business environment for road paving companies. Performance contracting and extended guarantee periods drive the companies towards improvement of product quality and process control. Since density of pavement is a key factor in strength and durability of the road surface, operational strategies are focus for research. The attention for this issue exposed that site operations and operational strategies are driven by "common practice" – the tacit knowledge and heuristics of the site crew built on years of personal experience (and often idiosyncratic). Building an objective picture of site operations is difficult since site operations are not documented. Knowing the exact location of compaction vehicles, their speed and their motion characteristics, can provide essential information for the understanding of asphalt pavement construction processes. This can be done using GPS technology. That is not straightforward. Experiments of such technology introduction show problems of adoption. To be adopted the technology should be tailored to the prevailing operational strategies, but at the same time the technology has to be adopted to make the prevailing operational strategies tangible. To overcome this causal dilemma an action research approach is chosen.

This action research approach provides opportunities for developing a framework to capture the operational characteristics of the compaction process in a more holistic manner. It diverts from previous process modelling studies where key role players have largely been left out of the process. Latham as cited in (Blockley and Godfrey, 2000) observed that "there is an acceptance that a greater interdisciplinary approach is necessary, without losing the expertise of individual professions." He recognised that all concerned with construction are interdependent and need to behave as a team. (Blockley and Godfrey, 2000) also argue that "we need to have a whole new view of process" and in order "to do that we need to include factors that are particularly needed when co-operation between people is important". The key issue here is that the operators need to be involved in, and take responsibility for the process. They are in fact largely responsible for the success of the process.

The action research methodology involves the researcher, innovative technologies and most importantly, the equipment compactor operators "driving" the compaction process. The first steps in this project show that the approach selected, taps into the enormous wealth of tacit knowledge and experience of operators – it provides insights necessary in analysing important operational characteristics in the asphalt compaction process. The unravelling and confronting of the practitioners view is expected to lead to improved control during the compaction process and consequently to improved product and process performance.

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