EVOLUTION OF AIRFIELD DESIGN PHILOSOPHIES

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ABSTRACT

Airfield loads and structural issues are significantly different from highways. For this reason, airfield design philosophy has evolved differently from the highway industry design approaches. This paper will examine how and why the airfield design approach has developed within the U.S. military as it evolved from its initial problems designing for the B-17 and B-24 during WW II to modern jet aircraft. The military design developed in parallel with civil U.S. design philosophy and with overseas approaches. This review will include rigid, flexible, and specialized military pavements.

INTRODUCTION

Airfield pavement design tends to be evolutionary rather than revolutionary. Each organization develops methods to meet their specific needs and to reflect their experiences. Differences between design methods promulgated by different organizations should be expected. This paper will examine the evolution of airfield pavement design concepts used by the U.S. military from primarily the perspective of the U.S. Air Force (USAF) and the Army Corps of Engineers (COE).

Several organizational factors influence military airfield pavement design and are worth noting at the start. Evolution of military aircraft drives the system. As planes get bigger, tire pressures increase, operational characteristics change, etc., the military airfield system must be adjusted to accommodate the changes. These changes tend to be rapid and dynamic, and military operations have been supported on every continent and on Arctic ice sheets. The military is responsible for the design, construction, use, and maintenance of their airfields which provides solid feedback on performance and problems. The military user is not shy about identifying deficiencies to their engineers. From the very beginning the military has used a combination of theory, full-scale, small-scale, and laboratory testing, and observation of in-service pavements to develop and adjust their airfield pavement design systems. The military has had a continuous systematic program of field evaluation of in-service airfields from the beginning, and this has provided invaluable insight into performance requirements. Also, boards of outside consultants have frequently been used and provided crucial input from academic and industry perspectives on military design issues.

The brevity required for this paper precludes depth. For more detail, one may consult Ahlvin (1991, 1971), American Society of Civil Engineers (1950), Barker and Brabston (1975), Department of Defense (2002), Hutchinson (1966), Parker et al (1979), Rollings (1981, 1988, 2001), Sale and Hutchinson (1959), Taboza (1977), Waterways Experiment Station (1951) as well as the specific references cited. Overlay design is covered in a companion paper for this conference (Rollings 2003).

TRAFFIC

Aircraft traffic tends to be less intense than major highway traffic, but the loads are far more severe. For example, a B-52 tire is more than fifteen times heavier than a truck tire and tire pressures are 4-1/2 times greater. The structural capacity of the airfield pavement must be far greater and the quality of the materials within the structure must be better to withstand the severity of such loads. Mindless substitution of materials or concepts from local highway practice on USAF airfields has led to numerous instances of unsatisfactory performance over the years. Such substitution is against policy but occurs periodically for economic considerations or procurement convenience or through ignorance. Designers and contractors should be well versed on airfield requirements; highway experience and practices are not sufficient.

Landing aircraft appear to impart a dynamic load to the pavement when they touch down. Initially, military airfield design engineers thought they should apply a dynamic impact factor much as bridge engineers do. In actual fact, stationary or slowly taxiing aircraft are the most severe load. This was initially established during WW II tests with an instrumented B-26 bomber at Wright Field, Ohio . These tests found that landing loads were only 40 to 60 percent of static loads, and dynamic gear loads greater than static could only be measured when the aircraft was flown into the pavement with such violence that the plane suffered mechanical damage (Rigid Pavement Laboratory 1943). U.S. Federal Aviation Administration (FAA) sponsored tests with instrumented pavement sections later provided comprehensive confirmation that stationary loading is the most severe loading on airfield pavements, and other operations (taxiing, touchdown, rotation) are less severe (Ledbetter 1976).

Aircraft traffic on a pavement is distributed over some width and is not concentrated in a single tire width. Accelerated traffic tests found that trafficking a single tire width caused less damage than distributing the traffic in three or more adjacent passes and the distributed traffic was more similar to what occurred in the field (Sacramento District 1942). These early observations led to the concept of coverages where multiple individual passes would be distributed over an area, and a coverage would be the maximum repetitions at a point. Design henceforth would be in coverages and not individual passes. Future more comprehensive traffic studies identified that aircraft follow a normal distribution, that civil and military traffic tends to fall into channelized or nonchannelized categories in different parts of the airfield differing only in their wander width, and that a aircraft pass-to-coverage ratio as a function of wander width and gear configuration could be used to convert anticipated traffic in terms of aircraft passes into coverages for design and vice versa (Waterways Experiment Station 1956a, 1960, Brown and Thompson 1973, HoSang 1975). Today pass-to-coverage ratios for channelized and nonchannelized traffic are available for a large number of aircraft on the PCASE web site maintained by the COE Transportation Systems Center of Expertise at Omaha, NE.

The airfields built during WW II showed initial distress in taxiways and runway ends where they were subject to slow taxing aircraft. This observation coupled with those just discussed led to designing different areas of the airfield for different traffic and load conditions. The most severely loaded areas were the primary taxiways and runway ends (Type A traffic area) designed for full aircraft load and channelized traffic. Parking ramps and similar facilities were designed for full aircraft load and nonchannelized traffic (Type B traffic area) recognizing their less concentrated traffic pattern. The runway interiors where aircraft speed was high and lift was in effect were initially made 10% thinner but later this was adjusted to design for 3/4 of the load and nonchannelized traffic (Type C traffic area).

Design of airfield pavements is in terms of coverages of the traffic. Common references to a 20-year life really mean that the number, load magnitudes, and types of aircraft expected in 20 years must be determined, the number of passes must be converted to coverages, dissimilar aircraft effects must be accommodated using equivalent aircraft conversions or Miner's linear cumulative damage hypothesis, and then the design calculations can be made. Passes appear on design aids such as computer program input or design charts but the actual criteria and calculations are always done in coverages though that may not be obvious to the user. Pavement life in terms of a specific number of years is really only technically appropriate for environmental durability issues, and design is actually always in terms of traffic loading.

Load magnitude dominates the airfield pavement design results so design usually only considers fully-loaded departing aircraft and ignores the lighter landing aircraft. Neglecting these lighter aircraft is also balanced to an extent by the fact that few aircraft routinely operate fully loaded.

WWII ORIGINS

In November 1940, the COE was assigned responsibility for design of military airfields and faced a serious problem. The B-17 and B-24 bomber aircraft in production had wheel loads of 18,000 kg and the B-29 that was on the drawing board was projected to be 70 percent heavier. All existing pavement design methods were based on highway experience, and none contemplated loads anywhere near this magnitude. In addition, the design methods had to be applicable worldwide, testing had to be simple but representative, and the method was needed right away. Responsibility for flexible pavement was assigned to the COE Waterways Experiment Station (WES) in Vicksburg, MS, rigid pavements to the Rigid Pavements Laboratory, COE Ohio River Division in Cincinnati, OH, and frost effects to the Frost Effects Laboratory, COE New England Division, Boston, MA. (By 1971 pavement management system responsibilities were assigned to the COE Construction Engineering Research Laboratory (CERL) in Champaign, IL, frost effects to the Cold Regions Research and Engineering Laboratory (CRREL) in Hanover, NH, and the remaining pavement work to WES; in 1999 all of the COE labs merged into the Engineering Research and Development Center).

Flexible Pavements. For flexible pavement design, the California Bearing ratio (CBR) was selected as the basic strength characterization concept after reviewing what was available in 1940. The test was simple, it could be implemented quickly, it had been correlated with service behavior since 1928, similar concepts had been used by two other states successfully, the subgrade strength could be easily tested at moisture and density conditions representative of final in-situ conditions, and it was as reasonable as anything else. A board of consultants composed of T. A. Middlebrooks, G. E. Bertram, O.J. Porter, and Arthur Casagrande had responsibility for extrapolating the existing highway criteria to these large B-17, B-24, and B-29 aircraft loads. The existing light and medium-heavy highway traffic curves were thought to be adequate for 1,800- and 3,200-kg aircraft wheel loads. The consultants went about this extrapolation in different ways but all relied on Boussinesq theory. They tried extrapolation based on maximum shear stress at pertinent depths for different loads, allowable deformation for different loads, and relationships between relative areas.

Combining the surprisingly similar extrapolations from these different approaches with some consensus judgements, the consultants developed a set of curves relating aircraft wheel loads from 1,800 to 32,000 kg to required pavement thickness for different CBR values. These were subject to further verification by full-scale accelerated traffic testing. However, with only minor adjustment in the high CBR range, these curves were used from June 1942 through 1949.

A comprehensive set of tests was conducted to standardize the CBR test into a form in which it could be used by the military (Waterways Experiment Station 1945). This work standardized test procedures, switched to dynamic rather than the older static compaction, standardized the modified compaction test in 1942, and developed the concept of soaking the samples to represent final in-situ moisture conditions.

The COE Tulsa District carried out an initial assessment of 4 possible asphalt concrete mix designs and concluded the Hubbard-Field method in October 1943. A WES study that began in 1943 and extended past the end of the war used laboratory and field tests to compare Hubbard-Field method with the Marshall method and select military asphalt concrete mix design concepts (Waterways Experiment Station 1948). This work found that the Marshall method was adequate to select asphalt content which was thought the most important parameter, was more compatible with military deployments than the cumbersome Hubbard-Field equipment, established test standards and criteria, concluded the 50 blow Marshall test was adequate for aircraft with up to 689 kPa tire pressure, and a low-quality base could be protected by increasing the asphalt concrete thickness.

Rigid Pavements. For rigid pavements, Westergaard's (1926) interior slab solution was found to correctly predict the form and shape of measured strains and make a conservative estimate of stresses in concrete slabs for aircraft loads in the interior of the slab. However, failure and higher stresses occurred at the edge of the slab. In 1943 the Corps had to issue a design procedure so the Westergaard analysis was used as a basis, but hefty factors of safety were needed and all joints had to be doweled or thickened edge to account for the unanalyzable edge load conditions.

In the formulation of Westergaard's equation the modulus of subgrade reaction, k, with units of a spring constant (kPa/mm or psi/in.) must be provided. Plate load test results are a function of the plate diameter. Tests conducted during this period by the Rigid Pavement Laboratory standardized the 0.762-m (30-in.) diameter plate as the best trade-off between usable k value and manageable size of the test plates. During this same period the third-point beam (ASTM C-78) test was accepted as the standard estimate for flexural or tensile strength of the concrete for concrete airfield pavements.

INTO THE COLD WAR (1945 through early 1970s)

This period saw the size of aircraft escalate and jets became predominate. The initial versions of the B-36 had a single-wheel load of 34,000 kg and trafficking tests were being run with single-wheel loads up to 90,000 kg in anticipation of aircraft that were on the drawing board. Fortunately, airplane designers switched to multiple wheels on a gear to reduce the individual tire load, but now the engineer had to determine the interactions between wheels. The introduction of jet aircraft also raised a new pavement concern - debris from spall, raveling, or delaminated material on the pavement posed a potential foreign object damage (FOD) hazard to the jet engines. Tire pressures also escalated. Many high-performance aircraft now had tire pressure that were approaching 2 MPa (the Navy F-4B meant to operate on carrier decks was 2.8MPa but it was not common on paved surfaces).

The introduction of the B-47 and B-52 in the 1950s brought several innovations. The nose gear was steerable, and the taxiways had painted center lines which led to unprecedented channelization of traffic. Also, the new aircraft were much easier to maintain than the old B-36 so more flights were made per aircraft. The combination of these factors led to pavements receiving their entire design lifetime traffic in short order - in less than a year in some cases. The resulting widespread pavement failures were an acute embarrassment for the military that led to several revisions to the design methods. Not all of these was well advised. The design load for the bicycle-geared B-47 and B-52 was increased 15% for a so-called dynamic load factor which also provided a greater factor of safety against a repeat of these embarrassing failures. As discussed under the traffic section of this paper, there is no technical basis for such a factor, and it was finally removed in 1981.

This was a period of major full-scale accelerated traffic testing to develop the concepts and criteria needed to deal with these aircraft changes. These tests included conventional pavements as well as special military issues such operations on unsurfaced or gravel surfaced fields and landing mat facilities. This was also the period when the COE's widely used soil and aggregate frost classification system was developed and the fundamental concepts of designing pavements for thawing conditions evolved (e.g., Berg and Johnson 1983, Department of Defense 2002). The worldwide deployment of U.S. forces to support the Cold War also led to extensive airfield construction on permafrost and innovations to avoid melting the permafrost.

Flexible Pavement. The introduction of the multiple-wheel gear assemblies required that some method be developed to deal with the overlapping stress cones of the gear tires. The Equivalent Single Wheel Load (ESWL) was the most viable approach to handling this issue for flexible pavements. In this concept, a single wheel load is substituted for the multiple wheels on the gear to achieve the same calculated response. By the early 1950s, experience with initial calculation methods for ESWL suggested a new technique was needed. Older data and new tests were used to compare different methods of calculating ESWL (e.g, vertical normal stress, maximum shear stress, and vertical deflection as calculated using Boussinesq theory). The vertical deflection appeared to be best and is the basis for the method still used to calculate ESWL for the CBR method (Waterways Experiment Station 1956, Taboza 1977). As aircraft gear configuration have become more complex with more wheels (C-5, B-777, and C-17) difficulties can arise in applying these Boussinesq derived deflection concepts.

With additional full-scale traffic tests after WW II, the CBR equation began to steadily evolve to include tire pressure effects and traffic repetitions (see Ahlvin 1991 for details). After the multi-wheel heavy gear load tests to develop criteria for B-747 and C-5 aircraft, the CBR equation reached its final form (Ahlvin 1971, Taboza 1977). Essentially, the thickness of material above a subgrade or material of interest that is needed to limit shear deformations is calculated as a function of the material's CBR value, the tire contact area of the load, alpha factor, and equivalent tire pressure (i.e., ESWL over tire contact area). The alpha factor was the last addition and relates the effect of coverages as a function of the number of wheels used to calculate the ESWL).

An eleven year study of moisture conditions in nonfrost conditions found that 3 to 5 years after construction, plastic subgrades under airfield pavements tended to reach an equilibrium moisture condition on the order of 95 to 98 percent of saturation with the degree of saturation tending to increase as the soil plasticity increased (Waterways Experiment Station 1948-1963). This supported the concept of soaked CBR for design analysis. Under arid conditions the plastic materials may be several percent drier so a pavement thickness reduction is allowed for arid areas (more than 4.6 m above water table and annual rainfall less than 380 mm). Where seasonal frost conditions must be considered a more explicit analysis of soil frost susceptibility, water availability, and frost penetration must be made to ascertain appropriate estimates of subgrade moisture contents and appropriate strength design values.

A component of a pavement may simply compact rather than shear, but an undesirable surface rut develops either way. Consequently, a design must protect against both shearing (provided by CBR equation) and densification. Data from test sections and in-situ pavements were used to establish the range of densities that pavement subgrade, base, and subase materials could reach under traffic as a function of a compaction index reflecting the intensity of the design requirement (Ahlvin et al 1959). Criteria were established for cohesive and noncohesive soils separately, and these criteria require compaction to levels equal to or above those that have been observed in the past under aircraft loads.

The high wheel loads and tire pressures of the B-47 and B-52 (coupled with the embarrassing failures mentioned earlier) led to proof rolling critical areas of flexible airfield pavements. This requires that once the surface of the subbase and each lift of the base have been compacted to 100% modified density by conventional rollers, they each will then receive an additional 30 coverages by a roller with wheel loads of 13,600 kg and tire pressure of 1.0 MPa. The previously mentioned compaction study had observed densities under large aircraft of 105% of modified-energy laboratory values and more. The proof rolling helps achieve this hard-to-specify goal and also identifies any soft or weak spots for repair before paving the surface layer. A recent study indicates this proof-rolling concept is still viable for high-tire pressure, heavy-load aircraft (Rollings and Rollings 2000).

The increase in wheel load and tire pressure caused widespread rutting in asphalt concrete in the years following WWII. A series of field studies, laboratory investigations, and accelerated traffic tests (e.g., Waterways Experiment Station 1962a, Brown 1974, Rollings and Ahlrich 1988, Ahlvin 1991) revamped the asphalt mix design concepts, and even a gyratory compactor was developed (Waterways Experiment Station 1962b) that aided in evaluation of mixes for very high tire pressure aircraft. The Marshall compaction effort was increased from 50 blow to 75 blow, voids and stability requirements were revised, and gradation, crushed particle content, field compaction and product control were drawn more tightly. These are the basis of the requirements used by the military (and FAA) today, and mixes placed to meet these requirements are performing well under modern aircraft in climates from the Tropics to the Arctic..

Rigid Pavements. The publication of Professor Westergaard's (1948) solutions for a load on the edge of a slab provided the key ingredient for powerful advances in rigid pavement design. His solution publication was quickly followed by Pickett and Ray's (1950) influence chart solution to Westergaard's original formulation and made solution easy and practical even for multiple wheel loads. Computerized solutions of these charts by Kreger (1967) as the H-51 computer code streamlined calculations even further. The accumulation of accelerated pavement tests eventually provided the basis for developing airfield rigid pavement design as a classical mechanistic fatigue analysis with its last revisions to the fatigue relation and calculation method in the early 1980s (Hutchinson 1966, Rollings 1981, 1989).

Several additional important design practices evolved and were incorporated during this period (Ahlvin 1991, Rollings 1981, 1989). Strain measurements in model, test track, and in-service pavements established that load can be transferred through dowels, keys, aggregate interlock, etc. from the loaded slab to the adjacent slab. While the amount of load transfer is a complex variable reflecting many parameters, these measurements suggested a 25% load transfer was a reasonable design allowance for the types of joints used on Air Force and Army airfields. Experience would find the keyed joint to be marginal, and its use on military airfields today is limited to light loading under favorable subgrade conditions. Accelerated trafficking of pavements with and without reinforcing steel found that the steel had no impact on when the crack formed but did improve post-cracking behavior. Except for conditions where cracking is expected (e.g., odd-shaped slabs) unreinforced concrete is the preferred concrete surfacing for rigid military airfield pavements. Observation of in-service pavements observed an often overlooked fact. While subgrade strength has only a modest impact on the calculated stress by Westergaard models and on behavior up to the initial cracking, post-cracking behavior is strongly influenced by the subgrade strength. A slab on a weak soil deteriorates much faster after cracking than does a similar one on a strong foundation. Earlier, it had been thought that the limited number of load repetitions on airfields made pumping. Experience showed was not so and by the mid 1950s, base courses were required when building on fine-grained soils.

This period also saw the design flexural strength shift from 28 days to 90 days to try to take advantage of the higher strength at 90 days. A runway at Selfridge AFB had massive problems with popouts soon after construction, and a bonded overlay had to be placed on the runway to control the FOD hazard. This experience led to a very significant tightening of aggregate quality requirements for USAF concrete pavements and has significantly impacted the cost of suitable aggregates in some locations.

FROM THE 1970S ON

The explosive growth of military aircraft size slowed during this period. However, improvements to aircraft engines, programs to stretch fuselages, etc. resulted in a steady increase in almost every model’s wheel load and tire pressure. The B-52 crept upwards, the F-15E model’s tire pressure soared to 2.3 MPa, the civilian DC-10 became the KC-10 tanker, the C-17 introduced a new untested complex gear.... The military pavement engineer’s job was not getting easier. Operational emphasis changed during this period, and there was a new emphasis on austere operating locations. Military operations needed criteria for stabilized surfaces, dirt surfaces, compacted snow surfaces, etc.

By this period, the venerable old CBR and Westergaard analysis approaches were showing their limitations. The complex gears were proving difficult, and the Boussinesq and Westergaard models upon which these systems were based theoretically did not handle certain classes of problems well: stabilized layers, thick layers of asphalt, overlays, or small nonstandard slab sizes as encountered in the old Soviet Union and its satellites. The rapid growth of the computer technology now made layered elastic solutions readily available to every engineers. By the end of the tail end of the 1980s, layered elastic design methodology was established and approved by the military as an alternate for the traditional CBR and Westergaard methods. Layered elastic methods were developed for pavement design and evaluation for flexible, rigid, and overlay pavements (Barker and Brabston 1975, Parker et al 1979, Rollings 1988). Even simple finite element programs capable of modeling the small precast slabs of the former Soviet Union were now available for use on portable computers in the field and were put to use by U.S. military engineers to assess pavement capacity in recent conflicts. Military research efforts in the late 1990s were pushing ahead with state-of-the-art finite element modeling of pavements, but operational emphasis has pushed this work to the back burner for the foreseeable future (Rollings et al 1998).

New material technology also blossomed during this period. Design procedures for unreinforced, conventionally reinforced, continuously reinforced, steel fiber reinforced, and prestressed concrete airfield pavements were all finalized and accepted for military use (summarized in Rollings 1981 and 1989). Roller compacted concrete, resin modified pavement, paving blocks, stone matrix asphalt, and polymer modified asphalts all required new design assessments as they were proposed for military use.

CLOSURE

Military airfield pavement design is in steady evolution to meet an ever changing kaleidoscope of problems. In this very brief review, we have seen how the initial introduction of a new technology (large bombers) forced the U.S. engineer to adapt and extrapolate inadequate existing knowledge to meet the design need. Where there was a void in the needed knowledge, theoretical analysis, laboratory, and full-scale tests coupled with observation of in-service pavements provided sufficient information to proceed until more work could provide better answers. However, neither the aircraft nor civil engineering technology remained stagnant. Advances in either (e.g., jet aircraft or Westergaard's edge-load model) stimulated new advances in the design process. It is the blend of theory, experimentation, and critical observation of field performance that allows progress. Any one without the others has poor prospect of success.

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