Special Report

By WALT MOORE, Senior Editor

Intelligent Compaction: Outsmarting Soil And Asphalt

North American jobsites are approaching this concept cautiously

Although the intelligent-compaction (IC) concept as applied to asphalt rollers has its critics, Bomag has a number of its BW190AD-4 HF models operating in North America with the company's Asphalt Manager, an IC system designed specifically for asphalt pavements. According to Bomag, the IC system works reliably in this application.

The quick — but not exactly complete — definition of intelligent compaction (IC) applies to vibratory rollers that automatically adjust their energy output, so as neither to under-compact nor over-compact materials. Thus, theoretically, IC yields precise and consistent results across the jobsite, while providing detailed documentation of compaction quality.

Are these not answers to the very petitions included in the prayers of all those responsible for compaction? Further, we're assured that IC is accepted as established technology in a number of western European markets. Might we reasonably expect, then, that roller users in North America are lining up to buy such machines?

So far, lines have been short on this side of the Atlantic. We hasten to add, however, that short lines at present indicate nothing negative, either about the technology or the machines available — or soon to be so — for North American jobsites.

At this writing, Ammann, Bomag and Dynapac all have IC machines ready for work in soil and aggregate, and Ammann and Bomag have asphalt models as well. Caterpillar plans to officially introduce an IC soil machine next year, and an asphalt model a year or so after that. Sakai's intentions are to be in the North American market with both types of IC rollers sometime in 2008, and Dynapac is developing an asphalt machine that will be available soon, says the company, first in Europe and then globally.

(Industry speculation is that Ammann will no longer market soil compactors in North America under its own name, but will supply these machines to a major U.S. manufacturer for marketing under that company's brand. Unclear at this point is whether this transfer will include IC soil machines. Our best intelligence says that Ammann will continue to market its asphalt machines in North America under its own name and, if so, Ammann's IC technology will remain available here.)

Although the estimated 20- to 30-percent price premium for IC models versus their conventional counterparts may be an issue for some users, slow sales at present seem more the result of the North American market still warming to the technology. Perhaps what's happening here is that the potential benefits of IC are so compelling, that those who stand to benefit from more precise, more consistent compaction want verification that the process can deliver what it promises.

Among those looking for the facts are the Federal Highway Administration (FHWA) and a growing number of state departments of transportation, Minnesota in particular. The FHWA now has in its hands a 160-page study — "Intelligent Compaction: Strategic Plan" — which details the technology and its potential benefits, identifies research needs and presents a national implementation plan.

The Minnesota DOT, in 2004 and 2005, extensively evaluated IC soil rollers from Bomag, Ammann and Caterpillar on state test sites, and continues to research the subject. According to John Siekmeier, P.E., senior research engineer in the Minnesota DOT's Office of Materials, certain of the state's roadway contracts in 2006 will require the use of IC machines on granular soils.

Also this year, both the National Cooperative Highway Research Program and the Transportation Pooled Fund Program will be starting studies regarding the use of IC rollers on soil structures, and the latter group's study also will encompass the roller's application in aggregate and on asphalt pavement.

Defining "intelligence"

For all of their sheer brute mass and power, vibratory soil and asphalt rollers have been getting smarter for decades.

In the mid-1970s, for example, Swedish manufacturer Geodynamik developed its Compactometer, a device (still being marketed in increasingly "smarter" versions) that measures the drum's movement and processes the resultant signals to provide a continuous relative value for a material's level of compaction or "stiffness." (Stiffness is loosely defined as a measure of a material's ability to resist deformation under load). This process has become known in Europe as "continuous compaction control" (CCC), and is widely used, along with a recording and documentation system that logs the measured values.

The Geodynamik system also reports drum frequency and monitors the "double-jump" condition, which occurs when the drum acquires so much energy that it begins to move upward during a vibratory cycle before hitting the ground, thus skipping every other impact. A machine operating in this manner may damage both itself and the material it's compacting.

The Geodynamik system and similar proprietary CCC systems, such as Dynapac's Compaction Analyzer (DCA), have gone a long way toward keeping the roller operator informed about the compaction process. And in some instances, these computerized systems are available with GPS assistance and can be retrofitted to existing units.

"Intelligent" innovations might also include, for example, the oscillatory-vibration system, which moves the drum in a rocking motion (versus conventional vertical vibration). According to Carl Pettersson, Geodynamik's managing director, the company initially developed the idea in the 1980s. More recently, Hamm has developed a proprietary oscillation-compaction system, which, says the company, prevents over-compaction by changing the drum's effort when material begins to firm. The system does this, says Hamm, by virtue of the physics designed into the drum's eccentric-weight system.

Also, in yet another display of intelligence, Ingersoll Rand's large DD-158HFA asphalt

The cab of this Bomag BW213-4 BVC roller, which is fitted with the company's VarioControl system — an IC system for soil machines, incorporates the machine's basic control panel (center), the VarioControl operating panel (lower right) and the Bomag documentation system (upper right).

The Geodynamik CompactoBar provides a continuous value relative to material stiffness. The basic technology behind this instrument is at the heart of today's intelligent-compaction systems. In the early 1990s, Geodynamik developed an IC system that adjusted not only amplitude and frequency, but also machine speed. The idea lost momentum, says Carl Pettersson, the company's managing director, because of market indifference and the cost of electronics at the time.

compactor allows the operator to select from a range of eight amplitude settings. Then, the machine automatically adjusts frequency "to the optimum performance setting."

As smart as the machines have become through the use of these and numerous other innovations, however, the "intelligent-compaction" process goes beyond preceding developments. Here's a definition synthesized from several sources:

An intelligent-compaction roller is a vibratory model that continuously measures and reports the stiffness of material, while simultaneously and automatically adjusting its compaction effort based on those measurements, imparting more energy to soft areas and less (or no) energy to hard areas. The roller also is equipped with a documentation system that allows real-time correction of the compaction process, while providing a permanent record of compaction results, including stiffness values for virtually every point in every lift.

Potential IC benefits

Among the potential benefits of IC rollers, says the FHWA study, is increased productivity, "because compaction energy is customized, based on measured stiffness. The result, says the study, "is a more rapid increase in compaction during initial passes, which may mean fewer passes to reach target values." The IC roller also may have the capability to compact deeper lifts, says the study, "because the magnitude of maximum amplitude that is used during the initial roller passes is significantly increased when compared with conventional rollers."

That last statement squares with what we heard from Bomag's Steve Wilson, marketing services/product manager, who told us that the Bomag BW213-4 soil compactor equipped with VarioControl, the company's IC system for soil machines, produces 82,000 pounds of centrifugal force at a 0.094-inch amplitude. This compares with the conventional 213's rating of 67,000 pounds at a 0.079-inch amplitude.

The results of potentially having to make fewer passes may include savings in time, fuel and machine maintenance. Some make the point, too, that because the IC roller's compaction forces diminish as material approaches target values, less energy (and less resultant stress) is reflected back into the machine's structures and drive train, thus potentially reducing wear and tear.

Hand-in-hand with increased productivity, says a Minnesota DOT study, is the prospect of improved compaction quality — on two fronts. First, because IC rollers have the potential to eliminate over-compaction and under-compaction, applying additional effort only if necessary, they actually are exercising a form of process control, similar, say, to a factory's computerized machining center, which constantly checks the quality of its own work. This control produces more uniform compaction, says the study, provided soils are within the moisture-content range necessary to achieve the target compaction.

"Second," says the study, "several demon-

Compaction Definitions

Exciter Mechanism: The system of rotating eccentric weights within a roller's drum that causes the drum to move in an off-center motion.

Frequency: The rotational speed of the exciter mechanism, typically measured in vibrations per minute (vpm).

Amplitude: A measure of the drum's movement, in thousandths of an inch, from its centered position. A drum that moves (or vibrates) vertically will travel as far above the surface as it does below the surface. In this instance, amplitude is usually reported as half the total travel.

Rotary Exciter: An exciter mechanism that causes the drum to move off-center in a circular or elliptical motion.

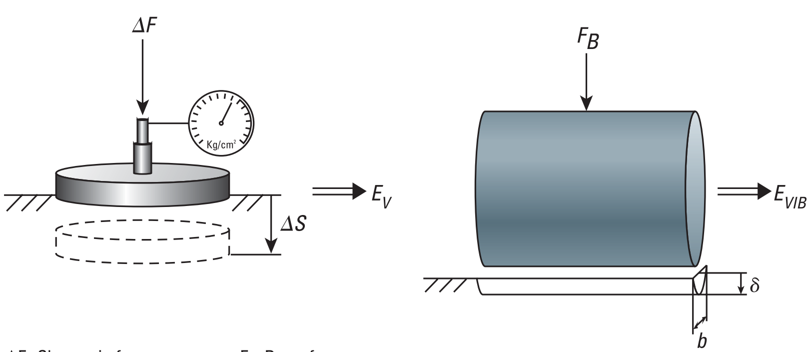
Oscillatory Exciter: An exciter mechanism that causes the drum to rock fore and aft on the surface.

Directed Exciter: An exciter mechanism that usually causes the drum to move vertically. (In some instances, the direction of movement can be changed through a 90-degree arc from vertical to horizontal.)

Double Jump: A condition in which the drum skips every other impact, because it has acquired so much energy that it begins to move upward during a vibratory cycle before hitting the ground.

stration projects have illustrated that compactors equipped with IC capability, like conventional compactors, cannot compact all soils under all conditions. Soils with moisture contents far from optimum, with soft or wet underlying materials — or other problems — cannot be compacted to target levels. Because of the surface-covering documentation that the IC roller provides, however, these problem areas may be identified and corrected before being covered by additional lifts." (Of course, a standard roller with a documentation system could also provide this benefit.)

Analogy of Bomag's "Vibration Modulus" (E_{VIB}) To "Deformation Modulus" (EV)



ΔF=Change in force
Δs=Change in subsidence

F_B=Drum force
b=Width of drum impression
δ=Subsidence

In our research, we came across a graphic depiction of how Bomag explains the stiffness value reported by its intelligent-compaction systems. The measurement is based on a soil-test procedure (the plate-loading test) that correlates force to ground deformation or subsidence. The Bomag measurement accounts not only for the depth of subsidence, but also for the area involved. We've modified the illustration slightly with the addition of the plate-loading mechanism.

Less checking, good records

Documentation provided by the IC process also offers the prospect of streamlining quality control. Since the IC roller automatically checks virtually every spot on the jobsite for compaction results, just a handful of manual spot checks may be required for confirmation.

Without this extensive verification, however, considerably more quality-control checks must be made (but still relatively few when compared with the IC roller's thorough coverage). Conducting numerous manual checks — whether by soil-replacement tests, asphalt coring or quick-reading gauges — can potentially be time-consuming, expensive and perhaps even risky on busy jobsites with a fleet of fast-moving construction machines.

Full documentation of compaction results also may serve as the contractor's proof of performance if pavement-warranty issues arise, and these documented results may be the basis, too, on which states potentially may award bonuses or assess penalties for compaction-work quality.

In addition, says Minnesota's Siekmeier, "intelligent compaction provides comprehensive data on the mechanistic properties of all materials compacted, permitting links between design, construction and performance. For example, the data record produced by the compactor, which covers all areas and all lifts, will be essential to the pavement-management process. Long-term performance may be correlated with the properties produced during construction."

Among the ultimate payoffs of the IC process, though, is the potential for creating structures that have longer useful lives. European experience, says the Minnesota DOT's research, "clearly demonstrates that greater compaction uniformity increases the useable life of pavement systems, and similar benefits occur with embankment compaction and buried-structure backfill."

Design generalities

Probably safe to say in regard to IC rollers generally is that most (but not all) use accelerometers (force/motion sensors) to measure drum movement relative to the machine frame, then employ proprietary software to calculate a stiffness value from these signals. Except for Sakai's proposed IC asphalt system, double-drum IC rollers use (will use) force-control for only one drum.

Although you'd have to take up the specifics with individual manufacturers, most would likely say that their measured stiffness values correlate well with accepted soil compaction tests, such as the Proctor method, provided soils are relatively homogeneous, granular in nature, and within acceptable moisture-content parameters. Some say also that their stiffness values for asphalt correlate well with commonly used density-measuring methods for this material, such as the Marshall test. But others, in truth, are still working on more closely determining the correlation between stiffness values reported for asphalt with those derived from conventional methods.

The IC system's software uses stiffness measurements (determined by the vibratory drum's reaction with the material beneath) as a reference for controlling the drum's energy imparted to the material. At least one manufacturer, however, is experimenting with an IC system that will not be based on drum vibration, but will instead correlate the drum's rolling resistance with material stiffness. If the system is found viable, it may allow the IC concept to extend to non-vibratory machines and may provide an alternative method for padfoot machines to determine stiffness values when working in cohesive soils.

In most instances, the recording and documentation systems that form an integral part of the IC package can be either the conventional type (requiring the operator to manually start and stop the recording process along a measured length of the jobsite), or the GPS-based or robotic-total-station-based type, which automatically provide centimeter-level positioning. As the IC process becomes more widely used, GPS-based systems likely will predominate, but conventional systems (or the ability to revert to a conventional system) will still be viable in areas not conducive to good GPS signals.

Ongoing investigation

Intelligent compaction is not without its critics, and much of that criticism is directed at the questioned effectiveness of IC systems working on asphalt pavements. For example, some contend that for compacting hot-mix asphalt, IC technology is not sufficiently developed to recognize the difference between stiffness created by an increase in the material's level of compaction, and that created by the cooling of the mix and the subsequent loss of asphalt-cement fluidity.

Others question the IC system's ability, when working on thin lifts, to distinguish between surface stiffness and that of underlying layers, whether base materials or previously placed mats. And, there are those who maintain that accelerometers, the basic sensors in IC systems, do not work effectively at measuring asphalt stiffness. Of interest here is the Geodynamik Asphalt Compaction Documentation (ACD) system, which uses proprietary algorithms, not accelerometers, to assess the compaction level of asphalt. Also, the Dynapac IC system for asphalt (currently being developed) will not use accelerometers.

Another criticism leveled at IC rollers is that they are unable to provide reliable stiffness measurements when the drum is in the process of adjusting its force. Proponents of the IC approach, however, counter that systems (which vary amplitude to vary force) are designed to select a "fixed" amplitude during the adjusting process and, thus, can be trusted.

Criticism aside, the combination of academic research, in-field experimentation and actual experience of contractors using IC machines — both on soils and asphalt — will surely, meticulously and objectively, help sort out the true capabilities of the IC process.

Measuring Compaction: Fundamental Changes

Adding to the scope of evaluating the IC process on North American jobsites is the related issue, being pursued by a growing number of engineers and researchers, of how best to measure a material's level of compaction.

On the soil side, for example, the widely used Proctor method, which determines "dry density" as an indicator of compaction, seems to be yielding ground to methods that instead measure material "stiffness," which is loosely defined as a measure of a material's ability to resist deformation under load.

Stiffness also seems to be the basis for calculating an even more fundamental material property, "modulus," which scientific types agree is the most accurate and independent means for judging deformation and, thus, a material's level of compaction. The modulus discussion is complex, and becomes even more so when dealing with the differences in granular and cohesive soils.

One of the most articulate investigators in this area is Jean-Louis Briaud, PhD, P.E., and professor of civil engineering at Texas A&M University, who has written extensively about soil modulus and has developed a measuring instrument, the Briaud Compaction Device (BCD), designed to quickly determine a value for soil modulus. If you're interested, a Google search for "Briaud Soil Modulus" will turn up several of his works, including those on modulus, the BCD and intelligent compaction.

Bomag

Bomag has two IC systems: VarioControl for soil machines and Asphalt Manager for pavement machines. The two systems are similar in that the exciter mechanism is contained within a housing that can be rotated through an arc of 90 degrees (via a slewing motor) to change the direction (vector) of the drum's force. As the material-stiffness-measuring system senses that compaction is increasing, the drum's force (which remains constant, because amplitude and frequency remain constant) is automatically vectored from a primarily vertical orientation to a primarily horizontal orientation.

Both Bomag systems, in their automatic mode, allow the operator to pre-set maximum compaction-force levels, and in their manual mode, the systems allow the operator to select from six exciter positions (force

The Minnesota Department of Transportation has been investigating intelligent-compaction soil machines for the past two years and continues to do so. The Bomag (pictured), fitted with the company's VarioControl system, was set up to run with a GPS-based documentation system on the Minnesota site.

values) to closely match material characteristics.

The value Bomag uses to report measured material stiffness is the "vibration modulus" or E_{VIB}, which, says the company, is measured in Mega-Newtons per square meter (MN/m^2). One Mega-Newton is equivalent to about 224,800 pounds of force. Bomag's Asphalt manager system also monitors mat temperature and allows parameters to be set in order to alert the operator when critical temperatures are approaching.

Although Ammann apparently will no longer market soil compactors in North America, a domestic manufacturer, already branding Ammann machines, may take on Ammann's IC soil machines and preserve the technology.

Ammann

Ammann defines its IC system, the Ammann Compaction Expert (ACE), as an electronic measuring and control system that automatically adjusts the amplitude and frequency of a vibratory roller to suit material characteristics. Thus, says the company, areas with lower "load-bearing capacity" are compacted with high effective amplitude, and hard areas with low effective amplitude. Amplitude is adjusted "as flyweights in the exciter system twist against each other," and frequency is adjusted "to the resonance of the ground."

Similar to the vibration-modulus value determined by the Bomag system, the ACE system determines "dynamic ground-bearing capacity" by equating the drum's action to a "plate-loading" test, in which a circular pad is pressed into the soil with a known force, and then the resulting deformation (or subsidence) in the material is measured. Ammann reports this measurement as the "kB" value, which is measured in MN/m.

When the ACE system is used on an asphalt machine, says Ammann, the first strip is compacted with the ACE system switched on, and a first kB value is determined (in relation to the subsoil) that can be memorized by the system. An infrared temperature gauge in the ACE asphalt system can prevent operation when the mix is "too hot, too cold, or when the material is in a critical temperature (tender) zone."

Dynapac

The Dynapac Compaction Optimizer (DCO) system, automatically adjusts the drum's amplitude "from zero up to a maximum, depending on the state of compaction." The DCO system most always should be operated in the automatic mode with maximum force values selected, says Dynapac, but the system does allow manual operation, and in that mode, provides the selection of six amplitudes or force values.

According to Ingmar Nordfelt, research manager for compaction and paving techniques at the Dynapac International High Comp Center in Karlskrona, Sweden, the Dynapac IC soil roller measures and reports a "dynamic stiffness value," identified as the Compaction Meter Value (CMV). The CMV, he says, has been used in Europe since the 1970s, and is a "well accepted and proven" indicator of the soil's relative state of compaction. The company's IC asphalt machine, currently being developed, will not use accelerometers to measure material stiffness, because Dynapac research, says Nordfelt, indicates that this approach is potentially unreliable.

Dynapac's IC system for soil machines reports measured stiffness values as a Compaction Meter Value (CMV), shown on the upper gauge.

Caterpillar's IC soil machine is planned for introduction in 2007 and will feature a GPS-based documentation system as standard equipment. The machine will adjust drum force by infinitely varying amplitude from zero to a pre-set maximum, and the system will automatically select from three frequency settings to match the amplitude band.

Caterpillar

Caterpillar calls the IC system being developed for its soil machines a "continuously variable amplitude" system, which can automatically adjust the drum's amplitude from zero to a maximum — a maximum that stays comfortably away from the double jump, says advanced product development manager Robert Ringwelski. But along with variable amplitude, the Cat IC system also will employ three frequency settings, one of which the system will automatically select depending on the amplitude range in which the drum is operating.

Adjusting the drum's force by varying the amplitude provides a huge advantage, says Ringwelski, because the zero amplitude setting allows the exciter system to remain spinning at all times. This means, he says, that the machine need not continually expend the tremendous energy required to restart the exciter's weights each time the machine reverses direction. Restarting the vibratory mechanism requires a significant amount of the engine's horsepower, he says, and requires that the exciter's hydraulic drive system run at near relief pressure until full momentum is achieved. All of this has the potential, he says, of allowing the use of smaller engines that use less fuel.

Geodynamik

Geodynamik's Asphalt Compaction Documentation (ACD) system is not technically (by our definition) classed as intelligent compaction, because it does not alter drum force. We include it here, however, because the system takes a different approach to measuring and reporting an asphalt mat's level of compaction.

The system, says Geodynamik, does not take into account the stiffness of the sub-grade, because the compaction value reported is not based on dynamic measurements taken by accelerometers. Instead, says the company, the ACD system uses a patented algorithm for calculating "compaction points," which are closely related to the energy imparted to the asphalt. The algorithm takes into account roller type, drum parameters, roller speed, temperature of the mat and time.

The calculated asphalt-compaction value (ACV) reported by the ACD system, says Geodynamik, also allows for the compaction effect from the paving screed and from static rollers. Thus, says the company, the ACV is related to the compaction energy imparted to the thin asphalt layer and is, therefore, not influenced by variation in sub-grade compaction quality.

Sakai

Sakai is presently testing IC machines, and according to the company, a working soil-roller prototype should be available for demonstration projects late this year. An asphalt model for demonstration should be available by mid-year 2007. The company plans to begin marketing the machines in North America sometime in 2008.

According to Sakai, the basic operating principle of its IC models is that of adjusting amplitude, and the stiffness values reported by these units will be based on a measure of the material's "dynamic modulus." Accelerometers are the basic sensors employed for both the soil and asphalt models, and on the latter, the IC system will be used in both drums. The Sakai systems will allow the operator to pre-set maximum force values when establishing compaction targets and, like most other competitive IC systems, will have provision for a manual mode.

According to Sakai, the basic operating principle of its IC models is that of adjusting amplitude, and the stiffness values reported by these units will be based on a measure of the material's "dynamic modulus."