17 Joint Construction

During the construction of HMA pavements, two types of joints are encountered. The first is a transverse joint, which is constructed whenever the paving operation is interrupted for a period of time—anywhere from 15 minutes to several weeks or more. The second is a longitudinal joint, which is built when a lane of HMA is constructed adjacent to a previously placed lane of mix. The techniques for constructing each type of joint are discussed in this section.

TRANSVERSE JOINTS

Suspension of Paving

The way a transverse joint is constructed depends primarily on whether traffic will be traveling over the asphalt mix before the paving is restarted. If traffic will not be passing over the end of the pavement, a vertical butt joint can be constructed; otherwise, a tapered joint must be built. In either case, the operation of the paver is essentially the same, but the construction of the joint itself is different.

It is important that the paver be run in normal fashion right up to the point at which the transverse joint is constructed. This means the head of material in front of the screed should remain as consistent as possible up to and at the location of the joint, so that the forces acting on the screed will be constant, and a consistent angle of attack will be maintained for the screed. The result will be a uniform mat thickness at the joint—the same thickness as that of the previously placed mix.

It is common but incorrect practice to empty out the paver hopper when a transverse joint is to be built. The paver operator runs the hopper out of mix, and the transverse joint is constructed at the point where the empty paver has stopped. As the hopper is emptied, however, the amount of mix carried on the augers is reduced until it is minimal. This process reduces the head of material in front of the paver screed, causing the screed angle to fall. The thickness of the mat then gradually decreases as the joint location is approached. The transverse joint is thus built at a low point in the new pavement surface, resulting in a dip that will be felt by traffic.

It is much better practice to locate the transverse joint at a point where the head of material in front of the screed is normal. This type of operation, however, requires more work on the part of the paving crew. If the joint is made where the pavement thickness (head of material) is constant, the paver screed is simply raised up at the point where the joint is to be built. Doing so leaves a great deal of mix on the roadway—the amount of mix that was in front of the screed. Except for the amount of mix needed to construct a taper, this material will have to be removed and then wasted or returned to the asphalt plant to be used as RAP. In addition, it will be necessary to dispose of the amount of mix remaining in the paver hopper. The advantage of this practice, however, is a smooth transition across the joint instead of a dip.

Butt Joints

For a butt joint (Figure 17-1), a vertical face is constructed by hand across the width being paved. This operation consists of raking, shoveling, and then removing the mix that is located downstream of the selected joint location. The mix thus removed is discarded or returned to the plant to be recycled. The mix that is in place upstream of the joint is not touched in any manner.

Compaction of the mix on the upstream side of the joint is accomplished in normal fashion. It is necessary, however, for the rollers to compact the mix immediately adjacent to the joint. For this to be done properly, runoff boards must be placed next to the joint. The thickness of the boards should be approximately equal to the compacted thickness of the layer being placed. In addition, the boards must be wide and long enough to support the full size of a roller. The compaction equipment passes over the mix at the joint and onto the boards before the rolling direction is reversed. This practice ensures that the transverse joint receives the same degree of compaction as the rest of the mix in the pavement layer.

If runoff boards are not used, the front wheel of the compaction equipment is normally run up to the transverse joint, stopping just short of the joint. The roller di-

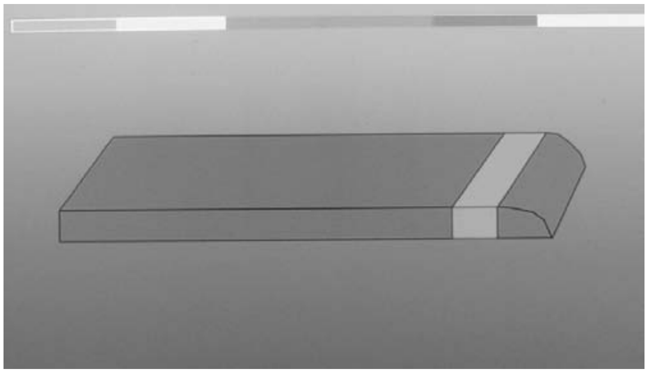

FIGURE 17-1 Construction of transverse butt joint.

FIGURE 17-2 Removal of material at butt joint.

rection is then reversed and the rest of the mat compacted. Occasionally, one wheel of the roller will be driven over the end of the course, over the vertical face of the joint. If a roller passes over the edge of the transverse joint with no board being in place beyond the edge to support the weight of the rollers, rounding of the edge of the joint will result. The extent of rounding will depend on the number of times the roller runs off the edge of the joint and the thickness of the layer being constructed. Two problems result in such cases. First, the rounding of the edge of the butt joint prevents the construction of a proper vertical joint face when paving is restarted. Second, the amount of compactive effort applied to the asphalt mix adjacent to (upstream of) the joint is typically inadequate. The lack of proper compaction in turn results in a high air void content in the mix upstream of the joint and a weak spot and dip in the pavement surface.

Runoff boards should therefore be used in the construction of butt transverse joints. If runoff boards are not used, however, one way to overcome the end-rounding problem is to cut back the mix to a location where the mat thickness is constant and the density meets specifications. This practice is illustrated in Figures 17-2 and 17-3. The rounded end of the butt joint is cut back, and the excess material removed and discarded. However, because no release paper has been placed under the mix that will be cut back and removed, it is often difficult to remove that mix. Thus the best practice is to build the transverse joint properly in the first place.

After materials have been removed and discarded, the area adjacent to the joint should be cleaned of all dust and other loose particles. The exposed edge should be lightly tacked with an acceptable tack coat.

Tapered Joints

If traffic will be passing over the transverse joint, a tapered joint or ramp must be built. For this type of joint, as for the butt joint, it is important that the paver operator keep the head of material in front of the paver screed as consistent as possible up to the point at which the joint is to be built to ensure that the thickness of the mix being placed will be uniform up to the joint. This can be accomplished more easily with a tapered than with a butt joint because a portion of the mix left in the paver hopper and in front of the screed can be used to build the taper.

At the location of the transverse joint, the asphalt mix downstream of the joint is temporarily pushed longitudinally away from the joint. A vertical edge is formed at the upstream face of the mix. If the taper is to be removed before construction continues, treated release paper or some similar material to which the asphalt mix will not stick is then placed downstream of the joint directly on

FIGURE 17-3 Application of tack at butt joint.

the existing pavement surface (see Figure 17-4). The length of the paper depends on the thickness of the course just placed, but is typically about 1 to 1.5 m (3 to 4 ft) and equal to the width of the lane being paved. If the paper is too short, the roller may tend to shove the mix, causing rounding of the joint at the upstream side of the paper. Once the paper is in place, the asphalt mix is shoveled back over it, and a taper is formed in this mix with a lute or rake. Any mix not used to construct the taper is discarded. If the joint is to be left in place permanently, the taper is constructed in the same manner, except that the treated paper is not used.

Sand or dirt from the edge of the roadway is sometimes used as a substitute for treated paper. This is not good practice. Although the sand or dirt does prevent the asphalt material in the taper from sticking to the underlying pavement surface, it is very difficult to remove the sand or dirt from the surface completely once the mix in the taper has been removed.

Typically, some of the bond-breaking material remains on the existing surface even after the surface has been swept with a hand broom. This dirty surface provides a slip plane for the new asphalt mix, and a shoving failure may occur at that point when the new pavement is subjected to traffic. This is true even if a tack coat is applied on top of the dirty surface to improve the bonding of the new mix to the existing pavement. Indeed, in many cases an extra amount of tack coat is applied near the joint to compensate for the dirt at that location. The extra material, particularly if not broken before the new mix is placed on it, can increase the chances for slippage at that point. Constructing a temporary tapered transverse joint using sand or dirt as the bond-breaking medium is therefore not acceptable paving practice.

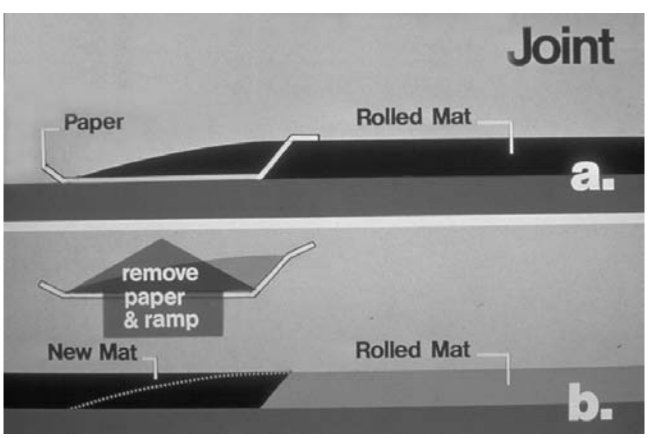

FIGURE 17-4 Use of treated paper in construction of tapered transverse joint.

Another type of tapered joint is the nonformed, sawed joint. For this type of joint, the paver operator keeps the paver operating normally until there is no more mix in the hopper or in the auger chamber. At the point where the mix becomes nonuniform across the width of the lane being paved, a taper is constructed with the leftover mix. No vertical face is formed, and the mix is merely tapered from the proper layer thickness to the level of the adjacent existing pavement. Any mix not needed to make the taper is removed and wasted. When it is time for construction to continue, a saw cut is made at the point at which the taper begins. All material from the taper is removed and wasted, although it is difficult to remove this material because it is typically bonded to the underlying layer (see the section below on "Removal of Taper"). As discussed further below, the vertical face where the saw cut was made should be treated with tack coat before construction continues.

One advantage of the tapered joint is the fact that the compaction equipment can run over the edge of the joint and down the taper without rounding the joint. Because the rollers can pass over the end of the mat easily, the compaction of the mix upstream of the joint is usually superior to that of the mix adjacent to a butt joint. A second advantage is that there generally is less mix to shovel from the joint because some of the extra mix is used to make the taper. The disadvantage of this kind of joint is that the mix must eventually be removed before paving restarts downstream of the transverse joint.

The length of a tapered joint is related to the thickness of the compacted pavement layer: the thicker the HMA lift, the longer the taper. Many agencies use a minimum ratio of 12 : 1 for the length of the taper and the thickness of the mat. For a mix that is 25 mm (1 in.) thick, therefore, the length of the taper should be at least 300 mm (1 ft). For a layer that has a compacted thickness of 50 mm (2 in.), the taper should be at least 600 mm (2 ft) long. This ratio allows traffic to travel safely from one pavement level to the adjacent higher or lower level.

Handmade Joints

In areas where the new HMA layer abuts an existing structure, such as a bridge deck, it is often necessary to place the mix adjacent to the joint by hand. The mix needed to complete the joint is deposited in the area to be paved either by the paver or by a haul truck. To avoid overworking the mix and possibly causing segregation, the mix should be placed as close as feasible to its final location. The mix is then spread by hand, using shovels, rakes, or lutes.

For such handwork, the mix must be left high to allow for compaction of the material by the rolling equipment. Because the mix is being placed by hand, it will not be as compacted as it would be if laid by the paver. Most paver-placed dense-graded HMA will compact roughly 6 mm (¼ in.) for each 25 mm (1 in.) of compacted mat thickness. Mix placed by hand, however, will be fluffier and not nearly as dense as machine-laid material. To permit proper compaction of the mix and ensure that it will be at the right elevation to match the adjacent structure, the level of the mix should be approximately 9 mm (⅜ in.) higher than the surrounding pavement for each 25 mm (1 in.) of compacted layer thickness.

The handwork area must be rolled by the compaction equipment as soon as possible after the mix is in the proper location. Because of the time required to place the mix, rolling will normally be delayed, and the mix will be cooling during the placement process. To achieve the required density, therefore, extra rolling may be needed.

Restart of Paving

Removal of Taper

If a tapered transverse joint has been constructed, the mix in the taper must be removed before paving can be restarted. For a taper built with treated paper, there is little bond between the mix in the taper and the underlying pavement. The paper and mix are readily removed and returned for recycling. A vertical face is left at the upstream edge of the joint.

As noted earlier, if a nonformed tapered transverse joint is built, a transverse saw cut must first be made in the asphalt mat where the taper begins. An advantage of this type of joint is that the saw cut can be made at any longitudinal point in the asphalt layer to ensure that the thickness of the layer is constant. Once the joint has been cut completely through the asphalt mat, a front-end loader is used to pry up the mix that is downstream of the saw cut. As discussed above, one disadvantage of this type of joint is that it is often very difficult to remove the mix from the existing roadway downstream of the saw cut. As an alternative, before construction resumes, a cold-milling machine can be used both to form the vertical edge of the transverse joint and to remove the mix in the taper.

A straightedge should be used to determine the condition of the transverse joint before paving begins. If the mix upstream of the joint is level, the location of the transverse joint is fine. If the straightedge indicates that the previously placed mix is not level, the location of the transverse joint should be moved upstream to a point where the pavement layer is of the proper thickness and smoothness. The mix downstream of the new joint location should be removed and discarded or recycled.

Application of Tack Coat

The existing pavement surface downstream of the transverse joint should be cleaned and made as free as possible of all loose materials and dust. As noted earlier, a tack coat should be applied to the vertical face of the transverse joint before paving starts (see Figure 17-3); the rate of application of the tack coat should be adjusted to the amount of dust remaining on the pavement surface. The tack coat should be permitted to break, but not necessarily set, before paving begins.

Use of Starting Blocks

As a rule of thumb, HMA is expected to densify approximately 20 percent under the action of compaction equipment. This means that the mix must be placed about 30 mm (1¼ in.) thick to produce a compacted mix that is 25 mm (1 in.) thick. This rule must be applied when the paver is used to place mix at a transverse joint.

If the layer being placed is to be 50 mm (2 in.) thick, the mix passing out from under the screed should be approximately 65 mm (2½ in.) thick to allow for compaction. It is therefore improper practice to set the paver screed directly on the old mat upstream of the transverse joint and start placing the new mix by dragging the screed off of the previously placed material. If this is done, an insufficient amount of mix will be placed on the downstream side of the joint, and a dip in the compacted pavement surface will result. Instead, proper paving practice requires that the paver screed be placed on a set of starting blocks, or strips of wood on the upstream side of the transverse joint. These blocks should be about 6 mm (¼ in.) thick for each 25 mm (1 in.) of compacted lift thickness, as stated above.

The starting blocks should be placed completely under the length of the screed, front to back, as illustrated in Figure 17-5. At least four strips of wood should be used for a standard screed up to 3.65 m (12 ft) wide equipped with rigid extensions. If the width of the screed with rigid extensions is greater than 3.65 m (12 ft), at least five or six blocks should be used, depending on the width of the screed. If the paver is equipped with hydraulically extendable screeds, either front or rear mounted, at least four blocks should be placed under the main screed and two additional blocks under each extension.

If the paver is starting out at a new location where there is no old mat on which to set the starting blocks

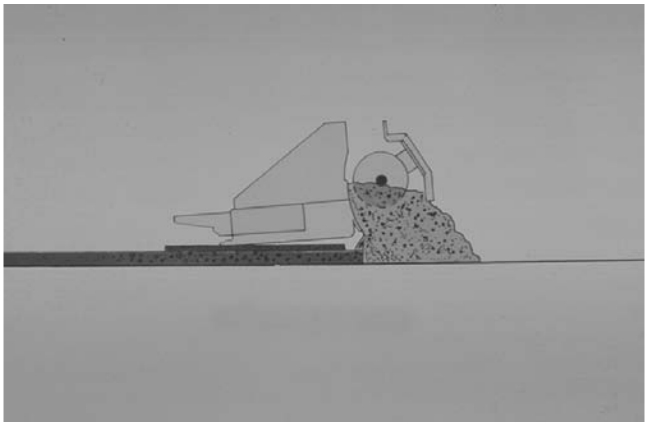

FIGURE 17-5 Use of starting blocks for paving at a transverse joint.

and screed, the thickness of the starting blocks must be increased to compensate for the lack of mix on the upstream side of the joint. In this case, if a compacted layer of mix 50 mm (2 in.) thick is being constructed, the blocks should be about 65 mm ($2\frac{1}{2}$ in.) thick to allow for the compaction of the mix by the rollers. For a compacted mat 75 mm (3 in.) thick, the starting blocks should be approximately 95 mm ($3\frac{3}{4}$ in.) thick. Thus the thickness of the starting blocks should be about 125 percent of that of the compacted HMA layer.

Nulling the Screed and Setting the Angle of Attack

After having been set on starting blocks of the proper thickness, the screed should be nulled. This means the screed's angle of attack should be set in the neutral or flat position. It should be possible to turn the thickness control cranks slightly in both directions when the screed is in the nulled position without putting any pressure on the screed and without setting its angle of attack.

Once the screed has been nulled, the angle of attack should be set. This is done by turning the thickness control cranks approximately one full turn (depending on the make and model of the paver) and introducing an up angle to the front of the screed. Both thickness control cranks or handles (one on each side of the machine) must be adjusted for the screed to be set properly.

Before the paver leaves the starting blocks, the material feed system should be activated and mix deposited in the auger chamber in front of the screed. To provide the proper head of material in front of the screed, enough mix should be deposited to cover the augers up to the center of the auger shaft. Once the auger chamber has been properly filled, the paver is started, the screed is pulled off of the starting blocks, and the paver is brought up to the desired laydown speed as quickly as feasible. As the paver moves down the roadway, the angle of attack of the screed is adjusted, as necessary, to provide the proper loose thickness of the asphalt mat. If the paver screed is nulled and the angle of attack set correctly while the screed is on the starting blocks, any necessary adjustment to the screed should be minimal.

Raking the Joint

If the transverse joint has been constructed properly up to this point, the amount of raking required will also be minimal, as shown in Figure 17-6. If the paver screed starts out on blocks and if the head of material against the screed is constant, the thickness of the mat downstream of the joint will be correct. Very little mix, if any, will need to be brushed back from the joint. There is never any reason to rake a transverse joint excessively (Figure 17-7).

When a joint is raked, there is a tendency for the raker to reduce the thickness of the new, uncompacted mat to match the elevation of the compacted pavement on the upstream side of the transverse joint by pushing the mix at the joint downstream farther onto the new mat. When the level of the new, uncompacted mat is the same as that of the old, compacted mat, however, the final elevation of the newly placed material, after compaction by the rollers, will be below that of the mix on the upstream side of the joint. The result will be a dip in the pavement surface at the transverse joint. Thus only minimal raking should be done.

Before the material on the downstream side of the joint is compacted, a straightedge should be used to determine whether the joint is smooth, as seen in Figure 17-8. The straightedge should rest on the uncom-

FIGURE 17-6 Raking of transverse joint.

FIGURE 17-7 Excessive raking of transverse joint.

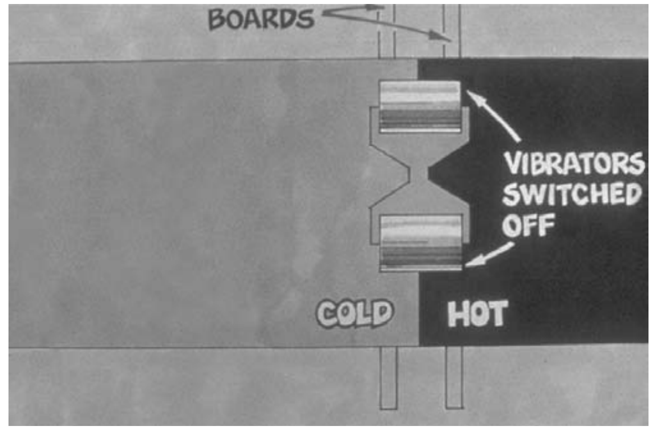

FIGURE 17-9 Horizontal rolling of transverse joint.

pacted mat and extend over the already compacted mix. The distance between the bottom of the straightedge and the top of the compacted mat should be equal to the amount of rolldown that will occur during the compaction process—approximately 6 mm per 25 mm (¼ in. per 1 in.) of compacted mat thickness. The straightedge should be used again to check the level of the joint once the compaction process has been completed. Obviously, the compacted mix should be level on both sides of the finished transverse joint.

Compacting the Joint

Ideally, a transverse joint should be compacted transversely (see Figure 17-9). This means the equipment used to roll the joint should operate across the width of the lane instead of longitudinally down the mat. If the rolling is done transversely, however, runoff boards must be used to support the roller as it moves beyond the longitudinal edge of the pavement. The roller should be operated so that the entire width of the joint receives equal compactive force. This is difficult to accomplish unless the wooden boards placed on each side of the lane are long enough to allow the roller to move completely off the mix on both sides of the pavement. Moreover, site restrictions, such as an adjacent guardrail or a steep side slope, may prevent the roller from operating in a transverse direction, and a safety problem is often created by operating the roller in a transverse direction if traffic is being maintained on the adjacent lane.

For these reasons, the transverse joint is usually rolled in the longitudinal direction (Figure 17-10). The initial (breakdown) rolling should be accomplished, however, as quickly as possible after the paver has moved off the

FIGURE 17-8 Checking smoothness at transverse joint.

FIGURE 17-10 Longitudinal rolling of transverse joint.

joint. The roller should pass slowly and completely over the joint before the machine is reversed. If the joint has been constructed properly, the compaction process for the transverse joint is no different from that for any other part of the asphalt mixture.

LONGITUDINAL JOINTS

Construction of the First Lane

Two key factors that affect the long-term durability of a longitudinal joint are built into the pavement during construction of the first lane. One is the importance of running the paver in a straight line so the joint can be matched on the next pass of the paver. The other is the need to properly compact the unconfined edge of the first lane (see also the detailed discussion of compaction in Section 18).

If the paver operator does not provide a straight line of mix that can be matched on the adjacent pass of the laydown equipment, it will be extremely difficult to construct a long-lasting longitudinal joint. It is suggested that the paver operator use a stringline to guide the paver as the first lane is being placed. In addition, if an extendable screed is used, its width must be kept constant; if the extendable screed is moved in and out, it will create an uneven edge that will be very difficult to match.

The compaction of the unconfined edge of the first lane is also extremely important. If the proper degree of density is not obtained in the first lane, the joint will deteriorate under traffic. It is critical that the roller make the same number of passes over the edge of the first lane as are made over the rest of the width of the lane. The edge of the drums of the vibratory or static steel wheel roller should extend over the free edge of the lane by at least 150 mm (6 in.). This practice will ensure that the compactive effort of the roller is applied in a vertical direction on the unconfined edge and will greatly reduce any tendency for the HMA mix to shove sideways during the compaction operation.

At no time should the edge of the drums of a vibratory or static steel wheel roller be located just on top of or just inside the unconfined edge of the lane. In either of these two positions, the mix may shove laterally under the forward movement of the roller, particularly if the mix is tender. If the mix does move, not only will the compaction of the mix adjacent to the unconfined edge be significantly less than required, but a dip will also be formed along the joint.

If a pneumatic tire roller is used in the breakdown position, the edge of the outside tire should not be placed either on top of or over the edge of the mix. Rather, the outside edge of the tire should be about 150 mm (6 in.) inside the unconfined edge of the mat. This will prevent rounding of the edge of the mat, prevent the mix from shoving laterally as a result of the high pressure in the pneumatic tires, and prevent excessive pickup when the rubber tires pass over the edge. Compaction of the mix at the unconfined edge must then be accomplished with a steel wheel roller, in either the vibratory or static mode.

It is important to note that most of the mass of a core cut from a longitudinal joint to measure joint density is actually taken out of the first lane of pavement, not the second. The unconfined edge of the mix that passes out from the end gate on the paver typically slopes at an angle of about 60 degrees. The mix placed in the adjacent lane is then laid against this slope. When a core is taken for density, however, it is typically drilled from the top of the joint that is visible at the pavement surface—half on each side of the joint line.

Cutting Back of the Joint

In some cases, before the longitudinal joint between two adjacent lanes of pavement is constructed, the longitudinal edge of the previously placed mix is cut back for a distance of 50 to 150 mm (2 to 6 in.). This is accomplished with a cutting wheel that is usually attached to a roller (Figure 17-11), but may be attached to a grader or front-end loader. The purpose of this operation is to remove that portion of the mix at the longitudinal joint that may have a lower density than the main portion of the mat because of the lack of confinement of the mix during the compaction process. This lack of density is normally due to improper overhang of the edge of the roller over the unconfined edge of the first lane during con-

FIGURE 17-11 Cutting wheel used to construct longitudinal joint.

struction. If the first lane is cut back, a tack coat should be placed on the newly exposed face of the longitudinal joint just before the adjacent lane is placed.

During this process, a vertical face, instead of the normal 60-degree inclined face, is formed at the longitudinal joint. This practice generally permits an increase in density to be obtained in the newly placed mat adjacent to the cut joint. Adequate joint density, however, can be obtained without cutting back the longitudinal joint—by properly compacting the first lane, as discussed above, and by properly overlapping and compacting the mix in the second lane, as discussed below.

Application of Tack Coat

If the free edge of the first lane is not cut back and the mix along the joint is clean, a tack coat is normally not needed. Although some agencies require that the edge of a longitudinal joint be tack coated before the next lane is constructed, many others do not. A tack coat along the joint, if not applied too heavily, should help create a bond between the two adjacent mats. On the other hand, there is no evidence that use of a tack coat significantly increases the durability of the joint under traffic. Other operational techniques generally affect the longevity of the joint more than the presence or absence of a tack coat.

Overlapping of the Joint

One key to the construction of a good longitudinal joint between lanes of HMA is the amount of overlap between the new and previously placed mats. The typical overlap at longitudinal joints is not more than 25 to 38 mm (1 to 1½ in.), as shown in Figure 17-12. This amount of overlap provides just enough material on top of the joint to allow for proper compaction without having extra mix that must then be pushed back from the joint by a raker. If properly done, however (see Figure 17-13), raking normally allows for increased compaction at the joint. The height of the new mix above the compacted mix should be 6 mm for each 25 mm (¼ in. for each 1 in.) of compacted mix.

As the mix is carried out to the sides of the paver by the augers, the HMA is pushed toward the end gate on the paver screed. Since the augers do not extend across the full width of the screed, however, the mix immediately adjacent to the end gate along the longitudinal joint is much less dense than the mix that passes under the main screed or the center portion of an extendable screed. In addition, because the mix at the end gate is not confined for as long a period of time as the mix that is along the interior of the screed, the mix at the former location is typically less dense. And because of the fluffier nature of the mix at the end gate, less mix is actually placed at that location. Consequently, many paver manufacturers have recently modified the design of the end gate to provide for greater confinement of the mix.

One problem that can occur with longitudinal joint construction is an excessive amount of overlap of the paver screed over the previously placed mat. This problem may arise because the screed operator simply has the end gate on the screed hanging too far over the first lane. It also may result, in part, from a ragged or wavy longitudinal edge on the first paver pass. Because the extra HMA cannot be pushed into the already compacted mat of the first lane, it is normally raked or luted onto the new mat. If the longitudinal edge of the first lane is straight and if the correct amount of overlap is used, the amount of raking required will be minimal.

The importance of putting the right amount of mix in the right place when constructing a durable joint cannot be overemphasized. If the amount of overlap of the first

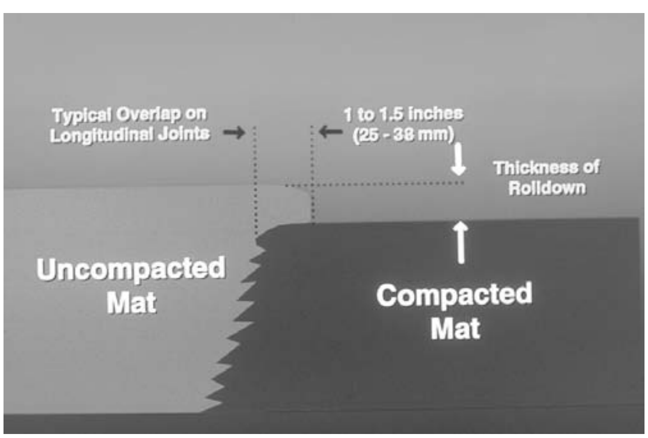

FIGURE 17-12 Thickness increase for uncompacted mix at longitudinal joint.

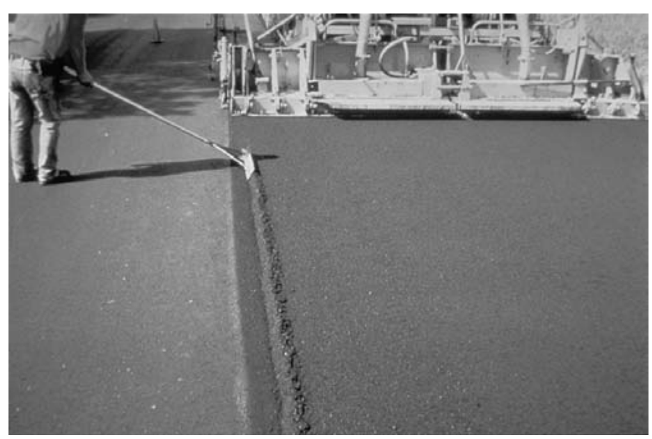

FIGURE 17-13 Raking of longitudinal joint.

lane is correct [no more than 40 mm (1½ in.) at the top of the joint] and if the height of the mix is correct [no more than 6 mm per 25 mm (¼ in. per 1 in.) of compacted mat thickness], there will be no excess mix to push away from the joint onto the new mat. The small amount of mix that overlaps the first lane will blend easily into the joint during rolling.

Raking of the Joint

There are those who believe it is always necessary to rake a longitudinal joint. As discussed above, however, if the right amount of mix is put in the right place, there should be minimal, if any, raking required. Raking may, of course, be required when driveway or mailbox turnouts are being paved, when an intersection is being constructed, or when it is necessary to match the grade of existing drainage inlets or manholes. As discussed earlier, however, raking should never be excessive, and the amount of mix moved should be consistent, especially along the longitudinal joint.

Some believe a raker should "bump" the joint, pushing the mix off the top of the first lane and onto the new mat directly over the joint, leaving a small mound of mix humped up for the rollers to compact. If too much material is left over the joint, the roller will tend to ride on the top of the hump and not come in contact with the adjacent mix, which also needs to be compacted. Further, because there is no place for this extra mix to go, a small bump usually remains along the joint after the compaction process has been completed. In addition, if the amount of mix overlapped on the first lane is not consistent, the volume of the bump created will be variable, and this variability will also affect the consistency of the joint density and evenness. Excessive mix at the joint is therefore not recommended.

Raking is generally not performed consistently. The rake or lute is typically used to push mix off the first lane and onto the new one. Sometimes the mix is deposited only a short distance from the joint, while at other times it is tossed halfway across the width of the new lane. If the adjacent lane is overlapped too far and too much mix is deposited on the old mat, the excess material should be pulled away from the joint instead of being pushed onto the new mix. The extra mix should not be broadcast across the new lane, but should be picked up and discarded. Better yet, it should not have been placed over the top of the first lane initially.

The raker typically places the rake or lute flat on the existing pavement surface, outside the edge of the new mix on top of the first lane. As the rake is moved transversely into the mix and across the top of the joint, all the mix is cleaned off the existing mat and pushed onto the new mat.

Because the raker does not lift the rake at the joint but moves the rake back and forth in a continuous sweeping or rocking motion, there is a lack of mix at the joint. The mix that should have been in place and ready to be compacted along the joint is now located partly across the width of the new mat. In most cases, the level of the uncompacted mix adjacent to the joint on the new mat is at the same elevation as the compacted mix on the other side of the joint. In some cases, so much mix is raked off the joint that a dip occurs at the longitudinal joint even before compaction of the mix begins. When either of these two problems occurs, it becomes impossible to obtain the required degree of density at the joint because there is not enough mix at the joint for compaction by the rollers. Moreover, when mix that is pushed off the longitudinal joint is deposited on the new asphalt mat, it changes the surface texture of the mat where it is deposited. Depending on the gradation of the mix being placed, the result can be a significant difference in the texture of the mat from one side of the lane to the other.

Excessive raking of the longitudinal joint is highly detrimental to the long-term performance of the joint because of the effect on the density along the joint. Excellent longitudinal joints can be constructed with minimal or no raking, if the proper amount of overlap of the new mix on the previously placed mat is achieved. It is therefore recommended that raking of the longitudinal joint be eliminated if proper overlap and compaction can be obtained.

Compaction of the Longitudinal Joint

If the level of the new, uncompacted mix is even with or below the level of the compacted mix in the adjacent lane, steel wheel compaction equipment will not be able to properly densify the mix along the joint. Whether the first pass of the roller is on the hot side of the joint or on the cold side (Figure 17-14), part of the weight of the roller drums will be supported on the previously compacted mat. As a result, the compaction equipment will bridge the mix at the joint, leaving it essentially uncompacted or only partially compacted. Thus, the level of the mix at the longitudinal joint must be above that of the compacted mix by an amount equal to approximately 6 mm for each 25 mm (¼ in. for each 1 in.) of

FIGURE 17-14 Starting compaction of longitudinal joint from the cold side, no longer a recommended practice.

compacted pavement if proper compaction of the mix at the joint is to be accomplished.

The use of a steel wheel roller, operated in either the vibratory or static mode, to compact the longitudinal joint generally results in bridging of the mix at the joint, and therefore a lack of density due to a lack of mix. Density can be obtained along the joint through the use of a pneumatic tire roller. The outside rubber tire on this type of compaction equipment can be placed directly over the mix at the joint. The compactive force applied by this tire can significantly increase the density obtained at that point. Nevertheless, a dip in the pavement surface will still occur along the joint if there is a lack of mix at that location. If proper density is to be achieved along the joint, there must be enough HMA there to compact, regardless of the type of roller used.

Rolling from the Hot Side

The most efficient way to compact a longitudinal joint is to place the roller on the hot (new) mat and overlap the joint by a distance of approximately 150 mm (6 in.) over the cold mat. The majority of the compaction equipment weight is where it is needed most—on the new mat. The mix at the joint is compacted into the joint area by the roller as long as the new mix at the joint is of the proper height. The slope along the edge of the first lane and the lower density of the mix placed beside the paver end gate provide the volume required for the mix to be blended in along the joint without leaving a hump at the joint. Any type of roller used for the breakdown rolling of the mix—vibratory or static steel wheel roller or pneumatic tire roller—can be used to compact the longitudinal joint as long as the elevation of the mix at the joint is above that of the cold mat and the new mix is still hot. Figure 17-15 shows a longitudinal joint being compacted with a pneumatic tire roller.

Sometimes the first pass of the roller is completed with the edge of the equipment about 150 mm (6 in.) away from the longitudinal joint (see Figure 17-16), in the belief that the mix will be shoved toward the joint by the roller, and better compaction will thereby be obtained. If the mix being placed is stable enough, however, the roller should not be able to move the material laterally to any significant extent. Thus if the mix design is proper, this method of compacting the joint provides no advantage over performing the first pass of the roller 150 mm (6 in.) outside the joint. Even if the mix is tender, there is no advantage to this method of compaction. If the mix can be moved laterally by the

FIGURE 17-15 Compaction of longitudinal joint with pneumatic tire roller.

FIGURE 17-16 Compaction with edge of equipment inside longitudinal joint.

roller, the mix design should be reviewed to determine whether a more stable mix can be produced. If the mix does move toward the joint, excess mix in the form of a hump will be present along the joint, resulting in turn in a lack of mix just outside the edge of the roller drum, between the roller and the joint. When the roller moves over to compact the mix at the joint, the drums will ride on top of the excess mix, trying to shove the mix back where it came from. With this procedure, the level of density obtained at the joint may be highly variable.

In summary, there appears to be no advantage to performing the first pass of the roller inside the joint by some distance. Lapping the roller over the adjacent old pavement typically is the most efficient way to provide roller coverage for the entire pavement width. Further, the overlap method provides for a more uniform density level at the longitudinal joint than does performing the first pass of the roller inside the joint.

Rolling from the Cold Side

In the past it was common practice to do the initial rolling of the longitudinal joint from the cold (previously placed mat) side of the joint, as seen in Figure 17-14. With this method, the major portion of the weight of the roller is supported by the cold, compacted mat. Only about 150 mm (6 in.) of the width of the roller hangs over the fresh mat, compressing the mix along the joint. The majority of the compactive force is wasted because the roller is essentially applying its compactive force to an already compacted HMA material.

While the roller is operating on the cold side of the longitudinal joint, the mix on the hot side of the joint, as well as the rest of the mix in the course being laid, is cooling. Depending on environmental conditions and the thickness of the mix being placed, compacting the joint from the cold side often hampers the ability to obtain the desired density over the entire pavement width.

The reason often given for rolling the joint from the cold side is that this method allows the rollers to "pinch" the joint so a greater degree of density is obtained. One edge of the roller drum rides on the new mix, while the other edge is in contact with the old mix some distance away across the first lane. More weight from the roller is thus applied to the new mix, which supposedly results in more density. Recent research, however, has indicated that the same density can be obtained at the longitudinal joint whether the initial rolling is accomplished from the hot or the cold side. Since it is more efficient to compact the whole mat, as well as the joint, from the hot side, compaction from the cold side is not recommended.

Regardless of the method used to compact the longitudinal joint, the level of density obtained at that location is typically at least 2 percent below the average density that can be produced in the main portion of the mat. This difference occurs primarily because the first lane has an unconfined edge that tends to move laterally. Even if the unconfined edge of the first lane is compacted, allowing the roller to hang over the edge, the density at the joint typically will still be less than that achievable in the main portion of the mat. If a particular level of joint density is to be required in the specifications, the percentage of the theoretical maximum density of the mix at the joint should be less than that required for the rest of the mat.

Wedge Joints

If traffic is allowed to cross a longitudinal joint before the second lane is constructed, some agencies limit the compacted depth of HMA that can be placed. In such cases, a wedge joint may be specified.

The wedge is usually formed during the first pass of the paver by attaching a metal form to the end gate of the paver screed. The degree of slope on the wedge varies, typically from 6:1 to 12:1 horizontally to vertically. The top of the wedge should have a notch so that sufficient material for compaction can be placed directly in the joint during the second pass. Formation of the wedge is not particularly problematic.

The cross slope of the wedge is different from that of the mainline mat. In addition, the wedge is quite narrow. Thus it is difficult to obtain adequate density on the HMA in the wedge before the adjacent lane is placed. If the rollers used to compact the rest of the mat width are used to compact the wedge, rounding of the edge may occur. This in turn will make it significantly more difficult to match the top of the joint when the next lane is constructed.

Different types of small rollers have been used to compact the mix in the wedge. Figure 17-17 illustrates one such attempt. In general, because of the lack of weight of this type of compaction equipment, it cannot be used to attain the desired level of density in the wedge material. However, when the adjacent lane is placed, the heat softens the wedge, allowing for some additional compaction.

Another potential problem associated with joints relates to the ability to match the joint uniformly when the adjacent lane is placed. There are two reasons for this problem. First, if the edge has been rounded during the compaction operation, the resulting ragged edge will be difficult to match with the second pass. Further, it will be necessary to feather out the mix in the new lane and attempt to blend that material into the mix in the first lane. Depending on the size of the aggregate incorporated into the mix, this feathering process may not be uniformly successful. When the second lane is placed and the mix is blended into the first lane, the larger aggregate particles in the mix will be exposed where the mix is feathered. The result may be a much rougher surface texture in the joint area and potential crushing of the coarse aggregate under the rollers. Significant raveling of the mix will then occur under traffic. Because of the feathering of the new mix into the old mix at the wedge joint, then, the performance of some wedge joints under traffic has been less than desirable.

One way to improve the performance of a wedge joint is to construct a short vertical face on the edge of the first lane before the wedge is formed. In this case, the depth and size of the wedge are reduced. Typically one-half of the uncompacted lift thickness is constructed vertically by a metal form attached to the end gate on the paver screed; the remaining thickness is shaped into a wedge by the same form. This type of wedge joint has several advantages. First, since the amount of mix in the wedge is reduced, there is less mix at the longitudinal joint with lower density than the full wedge joint. Second, because of the vertical face on the upper portion of the joint, it is easier to tie in the mix in the second lane without having to make a feathered joint. The potential for raveling of the new mix at the joint is thereby greatly reduced. Further, the surface texture of the mix at the joint is uniform since the mix does not have to be feathered, and the coarse aggregate in the mix will not be crushed by the rollers.

FIGURE 17-17 Compaction of mix in wedge joint.

The wedge joint built with a short vertical face also works well from the standpoint of traffic safety during construction. The key to good performance at the joint is to ensure that adequate density is obtained. The joint construction process should ensure good joint density.

Echelon Paving

If echelon paving (two pavers running next to each other in adjacent lanes) is used, construction of the longitudinal joint is changed so that the compaction of the unconfined edge of the first lane is delayed until the second lane is placed. The amount of overlap between the first and second lanes is also modified. The distance that the screed end gate of the trailing paver extends over the uncompacted mat behind the first paver should be no more than 25 mm (1 in.). The end gate of the second paver screed must be set at the same level as the bottom of the screed plate of the first paver. Doing so will prevent the end gate of the screed of the second paver from dragging on the mix placed by the first or leading paver and changing the surface texture of the mix in the area of the overlap.

No raking of the joint is needed. The compaction process is modified so that the rollers densifying the mix behind the lead paver are required to stay about 150 mm (6 in.) away from the free edge of the mat on the side toward the second paver. Once the mix from the second or trailing paver has been placed against the uncompacted edge of the mix from the first paver, the rollers compacting the second lane are used to densify the mix across the joint. With proper lapping and compaction, it is usually difficult to see the position of the longitudinal joint produced by the echelon paving process. In addition, use of this technique normally results in the density of the longitudinal joint being equal to that of the adjacent mat.

SUMMARY

The following factors should be considered in monitoring joint construction operations:

- If a transverse butt joint is to be built, the paver operator should maintain a constant head of material in front of the screed to a point downstream of the location where the joint is to be constructed. To prevent a decrease in the layer thickness upstream of the transverse joint, the operator should not be allowed to run the hopper, slat conveyors, and augers empty of mix before the joint location is reached.
- For the construction of a transverse butt joint, provision must be made for compacting the mix adjacent to the butt joint to the same degree as the previously placed mix without rounding off the end of the mix at the joint.
- For the construction of a tapered transverse joint, the thickness of the layer should be maintained to a point downstream of the location where the vertical face of the joint will eventually be constructed. Treated release paper, not sand or dirt, should be used as a bond-breaking material under the mix in the taper.
- When paving is restarted, the asphalt mix in the taper should be removed and then discarded or recycled. A vertical face should be present at the selected joint location, or the mix should be cut back to create a vertical face. A tack coat should be applied to the existing pavement surface at the joint location.
- The screed of the paver should be set on starting blocks on the cold side of the transverse joint. The thickness of the starting blocks should be 6 mm (¼ in.) for each 25 mm (1 in.) of compacted layer thickness when the blocks and paver screed are set on another pavement layer. If the paver is starting to place mix at a new location, the thickness of the starting blocks should be the same as that of the compacted new layer plus 6 mm per 25 mm (¼ in. per 1 in.) of compacted layer thickness. It is impossible to construct a proper transverse joint if blocks are not used to bring the screed to the proper elevation on the cold side of the joint before paving is started.
- The mix on the downstream side of the transverse joint must be higher than that on the previously compacted side of the joint to allow for adequate rolldown of the freshly placed mix.
- Minimal raking is needed at a properly constructed transverse joint.
- Ideally, a transverse joint should be compacted with the roller in a transverse direction. On a practical basis and for safety reasons, however, a transverse joint can be compacted properly with the roller running in a longitudinal direction as long as the initial elevation of the new mix is above that of the old mix on the cold side of the joint.
- To achieve proper density at the longitudinal joint, it is essential to compact the unconfined edge of the first lane correctly. The edge of the drum on a vibratory or static steel wheel roller should extend out over the edge of the mix a minimum of 150 mm (6 in.) when the first lane is being densified.
- During the construction of a longitudinal joint, the end gate of the paver should overlap the previously placed lane by no more than 40 mm (1½ in.). Any increase in the overlap beyond this distance will result in excess material that will need to be raked off of the joint. The new mix should be 6 mm per 25 mm (¼ in. per in.) thicker than the compacted mix.
- Minimal or no raking of the longitudinal joint should be necessary if the overlay of the paver screed on the adjacent lane is 40 mm (1½ in.) or less. The mix should not be bumped against the joint since it will then be impossible to blend the extra mix into the new mix during the compaction process. In no case should the raker broadcast the mix across the width of the new lane.
- Compaction of the longitudinal joint should be accomplished by rolling from the hot side of the layer with the roller wheels lapping approximately 150 mm (6 in.) over onto the cold mat. It is not recommended that the initial pass of the roller on the hot side of the joint be inside of the joint. It is much more efficient to have the first pass of the roller extend over the joint for a short distance onto the cold side of the joint.
- If a wedge joint is constructed, a short vertical face should be formed into the top of the joint to minimize the amount of mix contained in the wedge and permit the mix in the second lane to be placed and compacted against the first lane. This procedure will also minimize the amount of raveling that can occur at this type of joint if the second lane is feathered into the first.

18 Compaction

Compaction is the most important factor in the performance of an HMA pavement. Adequate compaction of the mix increases fatigue life, decreases permanent deformation (rutting), reduces oxidation or aging, decreases moisture damage, increases strength and stability, and decreases low-temperature cracking. An HMA mixture with all the desirable mix design characteristics will perform poorly under traffic if it has not been compacted to the proper density level. Indeed, a properly compacted mix with marginal properties will often outperform a mix with desirable properties that has been inadequately compacted.

DEFINITIONS

The *density* of a material is simply the weight of the material that occupies a certain volume of space. For example, an HMA mixture containing limestone aggregate might have a compacted density of 2355 kg/m^3 (147 lb/ft^3). This density, or unit weight, is an indication of the degree of compaction of the mixture. Paving materials made with different aggregates can have significantly different densities. An HMA mixture manufactured with lightweight aggregate, for example, might have a compacted density of only 1362 kg/m^3 (85 lb/ft^3).

Compaction is the process by which the asphalt mix is compressed and reduced in volume. Compaction reduces air voids and increases the unit weight or density of the mix. As a result of the compaction process, the asphalt-coated aggregates in the mix are forced closer together; this increases aggregate interlock and interparticle friction and reduces the air void content of the mix.

It is possible, under controlled laboratory conditions, to determine the density of HMA required to provide zero air voids. At this point, called the theoretical maximum density, no air voids would remain in the mix. Theoretical maximum density can be calculated from the percentages and specific gravity of each component of the mix. It can also be determined from a laboratory test, ASTM Test Method D2041, Theoretical Maximum Specific Gravity and Density of Bituminous Paving Mixtures, sometimes called the Rice test. The latter procedure is preferred for determining the theoretical maximum density compared with the mix component calculations.

On the roadway it is not possible to compact a well-designed mix to a voidless condition; therefore, all asphalt mixes will contain some air voids once the compaction process has been completed. The air void content of the mix is simply the volume of the spaces between the asphalt-coated particles. Because this volume cannot be measured directly, a ratio of the unit weight of the compacted mixture to the theoretical maximum density is used. Air void content is determined from the ratio of the bulk specific gravity of the mix to the theoretical maximum density as given by the following formula: percent air voids = 100[1 − (bulk specific gravity/theoretical maximum specific gravity)]. Thus if the bulk density is 95 percent of the theoretical maximum density, the mix has 5 percent air voids.

As an example, assume that the compacted density of an HMA mix is 2355 kg/m^3 (147.0 lb/ft^3) and that the maximum theoretical density of the same mix is 2467 kg/m^3 (154.0 lb/ft^3). The air void content of the mix will be the difference between the two values, 2467 − 2355 = 112 kg/m^3 (154.0 − 147.0 = 7.0 lb/ft^3), divided by the value of the maximum theoretical density of 2467 kg/m^3 (154.0 lb/ft^3), that is, 4.5 percent.

FACTORS AFFECTING COMPACTION

Four primary factors affect the ability of the compaction equipment to densify an asphalt mixture: properties of the materials in the mixture, environmental variables, conditions at the laydown site, and type of compaction equipment used. Each of these factors is discussed below.

Properties of the Materials

Aggregates

The compactibility or stiffness of an HMA mixture is influenced by the nature of the aggregate particles and aggregate gradation in the mix. Three properties of the coarse aggregate particles used in an asphalt mixture can affect the ability to obtain the proper level of density:

surface texture, particle shape, and number of fractured faces. With increases in aggregate angularity, nominal maximum size of the aggregate, and hardness of the aggregate (granite compared with limestone, for example), the compactive effort needed to obtain a specific level of density increases. Angular particles offer more resistance to reorientation by rollers than do rounded particles; hence, increased angularity increases resistance to densification from applied compactive effort.

The surface texture of the individual aggregate particles is also important. Aggregates that have a rough surface texture are more difficult to compact than aggregates with a smooth surface texture. The compactive effort required is affected as well by the shape of the aggregate. A cubical or block-shaped aggregate requires greater compactive effort than does a rounded particle before a given density level is achieved.

A continuously graded (dense-graded) aggregate, from coarse to fine, is generally easiest to compact. Open-graded or cap-graded mixes typically require a significant increase in compactive effort to obtain the desired level of density. An oversanded or finely graded mix, because of its inherent tender nature, may be difficult to compact.

Mixes that contain an excess of midsize fine aggregate [between the 0.60- and 0.3-mm (No. 30 and No. 50) sieves or between the 0.425- and 0.180-mm (No. 40 and No. 80) sieves] also are difficult to compact because of their lack of internal cohesion. These mixes tend to displace laterally rather than compress vertically. In addition, dust content [amount of aggregate passing the 0.75-mm (No. 200) sieve] affects the compactive effort needed. A mix designed with a high dust content will generally be more difficult to compact than one with a lower dust content, depending on the angularity and fineness of the dust particles.

In general, aggregates with properties that improve resistance to fatigue and permanent deformation require increased compaction effort to obtain a desired density.

Asphalt Cement

The grade and amount of asphalt cement used in a mix affect the ability to densify the mix. An asphalt cement that is higher in viscosity or lower in penetration will generally cause a stiffer mix at a given mix temperature, which will require a greater compactive effort to achieve density. Thus a mix produced with an AC-20 viscosity-graded asphalt will typically be stiffer, at a given temperature, than a similar mix containing an AC-10 asphalt cement. Within the PG binder classification system (see Section 3), a mix produced with a PG 70-22 graded binder will usually be stiffer, at a given temperature, than a mix produced using a PG 58-22 binder material. The stiffer the mix, the more compactive effort is needed to achieve a given density level.

The degree of hardening (aging) that occurs in asphalt binder during manufacture of the mix also affects the compactibility of the mix. Various asphalts age differently during the mixing process, depending, in part, on the chemical properties of the asphalt cement. Aging is also influenced by the type and operating characteristics of the HMA plant—more hardening will typically occur when a drum-mix plant is operating at partial capacity than when it is operating at full capacity. Moreover, higher manufacturing temperatures generally produce somewhat stiffer mixes.

The asphalt cement content of the mix also influences its compactibility. In general, a mix with too little asphalt cement may be stiff and require increased compactive effort, whereas a mix with too much asphalt cement will compact easily or may become tender and shove under the rollers.

Mix Properties

A mix that is at a higher temperature when laid [for example, 150°C (300°F)] will be easier to compact than a mix that is at a lower temperature [for example, 125°C (260°F)]. If the initial mix temperature is too high, however, the mix may be tender and difficult to compact until the temperature decreases and the viscosity of the asphalt binder increases. Conversely, if the mix temperature is too low at the time the initial compactive effort is applied, increased compactive effort will be needed to obtain the required density; indeed, the required density may never be achieved.

The workability of the mix is also affected by the temperature susceptibility (sensitivity of mix stiffness to temperature) of the asphalt cement. For highly temperature-susceptible asphalt binder, less time will be available for compaction because the mix will increase in stiffness more quickly with a decrease in temperature than mix containing a less temperature-susceptible asphalt.

The fluids content of the mix also affects the compactive effort needed. The fluids content is the sum of the asphalt cement content and the moisture content of the mix. If the amount of moisture in the mix from the plant is high (greater than 0.2 percent, by weight of mix), the extra fluids content will act like asphalt binder and may make the mix unstable and difficult to compact. Thus, the moisture content of plant-produced mix should be measured regularly. Most specifications require that moisture content be less than 0.5 percent, by weight of mix, when the mix is discharged from the plant. If the mix characteristics are marginal, however, a residual moisture content of as little as 0.2 percent may significantly alter the tenderness of the mix, and therefore its compactibility.

Environmental Variables

Research completed in the early 1970s determined the time available for compaction of various HMA mixes. The time available for compaction is defined as the time, in minutes, for a mix to cool from its laydown temperature when it passes out from under the paver screed to a minimum compaction temperature. Minimum compaction temperature for that study was set at 80°C (175°F). It was found that below this temperature, little density gain was achieved with the application of additional compactive effort. Any additional rolling with steel wheel rollers, except to remove roller marks, may result in fracture of the aggregate in the mix and a decrease in density. It is emphasized, however, that rolling should occur at as high a temperature as possible, given the properties of the asphalt mix, in order to achieve the required level of density with minimum compactive effort. At temperatures near 80°C (175°F), the probability of significantly increasing density or reducing air voids is very low. This lower cutoff temperature may vary somewhat with grades of asphalt.

In the 1970s study, six variables were found to have an effect on the rate of cooling: layer thickness, air temperature, base temperature, mix laydown temperature, wind velocity, and solar radiation. "Cooling curves," shown in Figures 18-1 and 18-2, illustrate the amount of time available for compaction under different combinations of these variables. For these two figures, it is assumed that the material being compacted is a dense-graded HMA mix. The surface temperature of the underlying pavement is assumed to be equal to the ambient air temperature. A constant wind velocity of 10 knots [about 18 km/h (11 mph)] and a constant degree of solar radiation are also assumed. The curves then show the estimated time, in minutes, required for the mix to cool from its laydown temperature to the minimum compaction temperature of 80°C (175°F) for different compacted layer thicknesses.

To use these graphs, three input variables are needed: initial mix laydown temperature, base surface temperature (assumed to be equal to the ambient air temperature), and compacted layer thickness. Figure 18-1 is to be used for mix laydown temperatures of both 121°C and 149°C (250°F and 300°F). Figure 18-2 is to be used when the mix laydown temperature is 107°C or 135°C (225°F or 275°F). The range of base temperatures for each set of curves is from −12°C to 15°C (10°F to 60°F). The range of mix layer thicknesses is from 13 to 150 mm (½ to 6 in.).

Layer Thickness

Layer thickness is probably the single most important variable in the rate of cooling of asphalt mixtures. Dur-

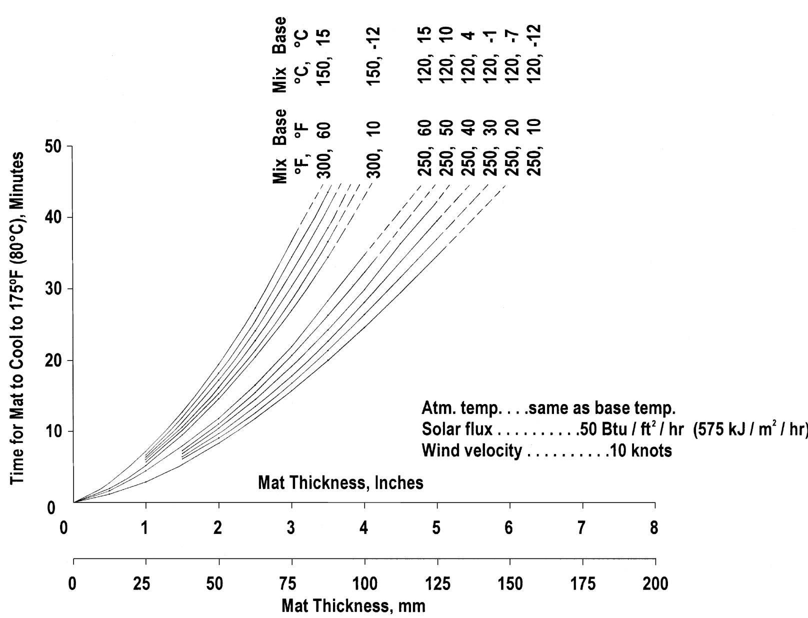

FIGURE 18-1 Time for mat to cool to 80°C (175°F) versus mat thickness for lines of constant mix and base temperatures [121°C (250°F) or 149°C (300°F) behind paver].

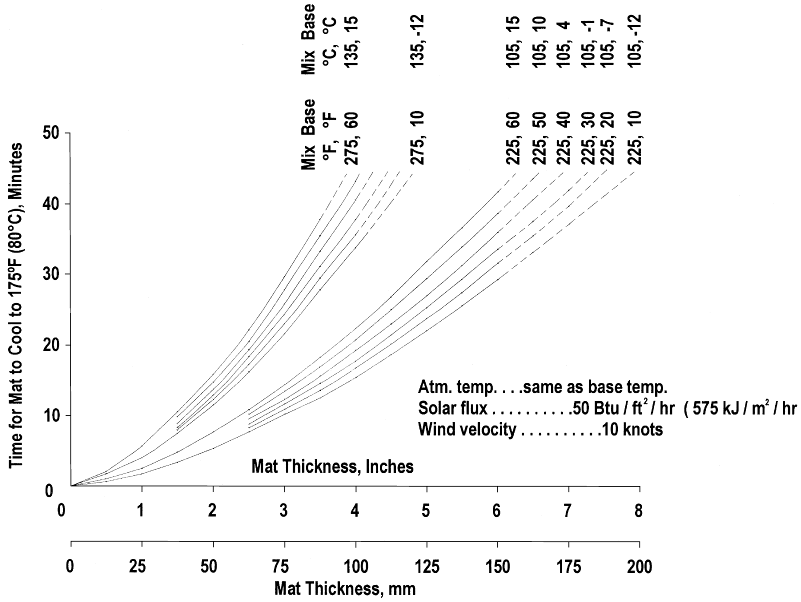

FIGURE 18-2 Time for mat to cool to 80°C (175°F) versus mat thickness for lines of constant mix and base temperatures [107°C (225°F) behind paver].

ing early spring and late fall, thin lifts are difficult to compact properly. Layers of mix less than 50 mm (2 in.) in compacted thickness are highly susceptible to premature failure because of the inability to densify the mix adequately before it cools. The desired density is very difficult to obtain on thin lifts of mix in cool weather because of the mix's rapid decline in temperature.

As the thickness of the layer being placed increases, the time available for compaction also increases. For example, referring to Figure 18-1, for a mix laydown temperature of 121°C (250°F) and a base temperature of 5°C (40°F), a mat 25 mm (1 in.) thick will cool to the 80°C (175°F) compaction cut-off temperature point in less than 4 minutes. For a layer 50 mm (2 in.) thick under the same mix and base temperature conditions, it will take about 10 minutes for the material to cool to 80°C (175°F). Doubling the lift thickness from 25 to 50 mm (1 to 2 in.) increases the time available for compaction from 4 to 10 minutes. If the layer depth is 100 mm (4 in.), the time to cool becomes about 29 minutes, a significant increase in available compaction time under similar temperature conditions.

Referring again to Figure 18-1, the relative effect of pavement lift thickness is the same for a mix laydown temperature of 149°C (300°F) and a base temperature of 5°C (40°F). As the depth is decreased from 100 to 50 to 25 mm (4 to 2 to 1 in.), the time available for the mix to cool from 149°C (300°F) to 80°C (175°F) decreases from more than 40 to 16 to only 6 minutes, respectively. From these data, it is apparent that the time available to compact a thin layer of HMA is extremely limited in cold weather.

Air and Base Temperature

A portion of the heat in the asphalt layer is lost to the air. Heat is also lost to the layer on which the new material is placed. Cooling of the mix near the base is more rapid than near the surface. Thus, base temperature is actually more important than air temperature in determining the time available for compaction.

Most specifications require a minimum air temperature for paving and compaction operations. It is often assumed that air and base temperature are the same. This is not necessarily true, particularly in cool weather. In early spring, the base temperature (surface temperature of an existing pavement layer) will be lower than the ambient air temperature early in the morning. The air temperature might be 5°C (40°F) and rising, but the base temperature might be 3°C to 6°C (5°F to 10°F) below the air temperature. The low base temperature will reduce the time available to achieve adequate density. On the other hand, base temperatures are often higher in the late fall than in the early spring for the same overnight air temperature. Thus, a given thickness of material is easier to compact in the fall than in the spring for the same air temperature conditions.

A moist base layer significantly increases the cooling rate of the new overlying asphalt layer. Heat is lost from the mix to the moisture, turning water into steam and increasing the rate of heat transfer. Paving on a wet surface therefore hampers the ability to gain proper density in the mix.

As the temperature of the ambient air and existing pavement surface increases, the time for the mix to cool from the laydown temperature to 80°C (175°F) also increases. Referring to Figure 18-2, for a mix temperature of 135°C (275°F) and a lift thickness of 75 mm (3 in.), it takes only 22 minutes for the mix to cool when the base and air temperatures are both –7°C (20°F). The time available is extended slightly to 25 minutes for a base/air temperature of 5°C (40°F) and to 30 minutes for a base/air temperature of 15°C (60°F).

Again referring to Figure 18-2, for a lift thickness of 50 mm (2 in.), using the same mix laydown temperature of 135°C (275°F), the time to cool to 80°C (175°F) increases from 11 to 13 to 15 minutes for a base/air temperature of –7°C, 5°C, and 15°C (20°F, 40°F, and 60°F), respectively. Thus the temperature of the ambient air and base surface is important, though not nearly as important as mat lift thickness, in determining the time available for compaction.

Mix Laydown Temperature

Asphalt mixes are usually produced at temperatures between 130°C and 165°C (270°F and 325°F). Depending on environmental conditions and the length of the haul, the mixture can decrease in temperature from 3°C to 14°C (5°F to 25°F) between the plant and the paver. The plant mixing temperature is not important in determining the time available for compaction, but mix temperature as it comes out from under the paver screed is. As the initial mix laydown temperature is increased, the time available for compaction also increases. Thus within limits, the mixing temperature should be determined by the laydown and compaction temperature requirements.

Referring to Figure 18-1, for a lift thickness of 50 mm (2 in.) and a base/air temperature of 5°C (40°F), the time to cool to 80°C (175°F) increases from 9 to 16 minutes as the laydown temperature increases from 121°C (250°F) to 149°C (300°F). For a lift thickness of 100 mm (4 in.) and a base/air temperature of 15°C (60°F), a change in laydown temperature from 149°C (300°F) to 121°C (250°F) reduces the time available for compaction from 36 to 21 minutes.

The effect of mat laydown temperature is more significant for thinner mats and lower base temperatures. As the time to cool to 80°C (175°F) becomes shorter, an increase in the mix laydown temperature extends the compaction time significantly in most cases.

Wind Velocity

A thin layer of mix will cool more quickly when there is a strong wind than when there is little or no wind. Wind has a greater effect at the surface of the mix than within and can cause the surface to cool so rapidly that a crust will form. This crust must be broken down by the rollers before the compaction process can begin. The velocity of the wind is more of a concern for thin layers of mix placed in cool weather than for thicker layers laid in warmer weather.

Solar Flux

The amount of radiant energy available from the sun (solar flux) depends on many variables, including the position of the sun above the horizon, the distance above sea level of the paving project, the amount of haze in the air, and the degree of cloud cover. A mix will cool more slowly on a sunny than on a cloudy day. The amount of solar flux has more effect on base temperature than on mix temperature. For a given ambient air temperature, the base temperature will be higher on a sunny day than on a day with heavy cloud cover. The higher base temperature will reduce the rate of cooling of the mix and increase the time available for compaction.

Obtaining Proper Density Under Varying Environmental Conditions

Compaction of asphalt mix requires common sense. If lift thickness, air and base temperatures, laydown temperature, or solar flux decreases or the wind increases, less time will be available to obtain the required level of density before the mix cools to 80°C (175°F). Thus a significant change in any one of these factors can make the difference between constructing a durable pavement and building one that will be subject to early failure.

If possible, the best solution to a potential compaction problem is to increase the thickness of the material being placed. A layer 25 mm (1 in.) thick cools so quickly, even in good environmental conditions, that proper density is difficult to obtain. The minimum course thickness that should be specified under the best of circumstances is 38 mm (1½ in.). For paving conducted in early spring or late fall, at least 50 mm (2 in.) of compacted asphalt mix should be placed in a single lift, if possible.

The easiest solution to a potential time availability problem is to increase the discharge temperature of the asphalt mix at the plant, if doing so does not cause other problems with the mixture. The higher discharge temperature will permit an increase in the laydown temperature of the mix behind the paver screed, thereby allowing more time for the mix to cool to 80°C (175°F), all other factors being constant. It is also important to remember that as temperature rises, aging of binder and absorption increase, so increasing the mix temperature requires careful consideration. Increasing the mix temperature may not be enough, however, to provide adequate time for compaction under adverse environmental conditions and for thin layers of material. If the mix temperature is increased too much, the mix may be tender under the compaction equipment, and smoke or other emissions may become a problem. The mix must then be allowed to cool before the compaction process can begin. Thus there is an upper limit to the temperature increase to which the mix can be subjected.

Compaction effort can be increased simply by using more rollers to compact the pavement layer. In addition, wider or heavier rollers can be substituted for narrower or lighter equipment. A double-drum vibratory roller, for example, that is 2.1 m (7 ft) wide can be used in place of a static steel wheel tandem roller that is only 1.4 m (4½ ft) wide.

Another means of achieving desired compaction levels is to use the compaction equipment more effectively. Depending on the width being paved and the width of the rollers, the rollers can be placed almost side by side instead of end to end. Two rollers running in this fashion can cover a given area much more quickly than two rollers operating in the conventional manner. Density will increase because more compactive effort can be applied before the asphalt mat cools to 80°C (175°F). In essence, this method provides for two breakdown rollers instead of one breakdown and one intermediate roller. To obtain the required density levels, however, use of an intermediate roller or rollers may still be necessary. Increasing the speed of the rollers is not a good means of improving compaction. Two passes at high speed are less effective than one pass at half the speed.

If two different types or sizes of rollers (such as a vibratory and a pneumatic tire roller) are used for echelon rolling, it is important that each roller cover all of the mix surface. This may mean that the rollers must cross back and forth and run different roller patterns and numbers of passes. In addition, if one of the rollers is compacting a longitudinal joint, this must be considered in setting the rolling pattern for each piece of compaction equipment. It is very important that all rollers be able to keep up with the speed of the paver and that the density obtained be measured to ensure that the required level of compaction is achieved uniformly across the width of the mat.

One procedure that should *not* be used in an attempt to increase the level of density in the mix is to increase the asphalt cement content of the mix arbitrarily. Although the additional asphalt cement may be beneficial in increasing the workability of the mix, it defeats the purpose of mix design and has been linked to long-term performance problems for the mix under traffic, such as rutting and shoving.

Laydown Site Conditions

A number of factors at the laydown site directly affect the ability of the compaction equipment to create the required level of pavement density. As discussed previously, the most important of these factors is the thickness of the layer being placed. The relationship between lift thickness and nominal maximum aggregate size in the mix is also important. If the course depth is at least three times the nominal maximum aggregate size, adequate density can be achieved with normal compactive effort.

Uniformity of lift thickness is another factor to be considered. Density is much easier to obtain in an asphalt layer that has a constant thickness as compared with one that varies in depth. A variable thickness layer is often difficult to densify to a given air void content uniformly, especially when placed over a rutted or uneven pavement surface. Static steel wheel rollers tend to bridge over ruts, particularly if the ruts are relatively deep and narrow. Vibratory rollers tend to be supported by the high points in the surface, although the vibratory action has some beneficial effect in compacting the mix in the ruts. Thus adequate density is usually not obtained throughout the mix with steel wheel rollers, particularly in rutted areas where it is needed the most. Use of a pneumatic tire roller is very helpful in achieving density in both ruts and high spots if proper tire inflation pressure and wheel load are used.

Compaction Equipment

The type of equipment used to compact the asphalt mix obviously has a significant effect on the density that can be obtained with a given number of passes. Three primary types of self-propelled compaction equipment are currently being used—static steel wheel rollers, pneumatic tire rollers, and vibratory steel wheel rollers. A combination roller, equipped with both a vibratory drum and a set of four pneumatic tires, is also sometimes used.

Static Steel Wheel Rollers

Static steel wheel rollers, shown in Figure 18-3, normally range in weight from 2.7 to 12.7 tonnes (3 to 14 tons) and have compression drums that vary in diameter from approximately 1.0 m (3.3 ft) to more than 1.5 m (5 ft). The gross weight of the roller can usually be altered by adding ballast, but this adjustment cannot be made while the roller is operating and is not normally made during the course of a paving project. For this type of roller, both the gross weight of the machine and the contact area of the drums with the mix are important in determining the compactive effort applied by the roller to the surface of the new mat.

Effective contact pressure, in terms of kilopascals (kPa) [pounds-force per square inch (psi)] over the contact area, is the key variable for this type of equipment and is dependent on the depth of penetration of the drums into the mix: the greater the depth of penetration, the greater is the contact area and so the less is the contact pressure. Thus on the first pass of the roller, when the indentation of the drums into the mix is the greatest, the roller exerts less compactive effort on the mix. On subsequent passes as the mix becomes more dense, the drums penetrate to a lesser degree, and the compactive effort of the roller is increased.

Drawbar pull is defined as the horizontal force required to move the roller forward. The most efficient roller is that with the smallest drawbar pull. Rollers with large-diameter drums have lower drawbar pull (rolling resistance) because they do not tend to penetrate as far into the mix to develop a contact area as a roller with smaller-diameter drums.

Once the size and weight of a static steel wheel roller have been selected, the variables under the control of the roller operator are the speed of the roller, the position of the roller on the mat in relation to the paver, operation with the drive wheel or drum toward the paver, and the number of passes made with the roller over each point in the pavement surface.

Pneumatic Tire Rollers

Pneumatic rollers are usually operated in the intermediate roller position, behind a vibratory or static steel wheel breakdown roller and in front of a static steel wheel finish roller. Pneumatic rollers are sometimes used, however, for initial rolling of the mix, and occasionally for finish rolling.

For a pneumatic roller, shown in Figure 18-4, the compactive effort applied to the mix is a function of the wheel load of the machine, the tire pressure, the tire design (tire size and ply rating), and the depth of penetration of the tires into the mix. All of the tires on the roller should be the same size, ply, and tire pressure. The area of each tire footprint and the wheel load of the roller are the primary factors in the effectiveness of a pneumatic tire roller. The greater the contact pressure between the tire and the mix, the greater is the compactive effort applied by the roller.

To be effective when used in the breakdown roller position, rollers with larger tires should be used. Rollers equipped with tires 7.50 × 15 or smaller are normally not effective as breakdown rollers. If pneumatic tire rollers are used as intermediate rollers, the minimum tire ply rating should be 12, and the tire pressure should be 400 kPa (60 psi) or greater.

The tire pressure used depends in part on the number of plies in the tires. In general, a 6-ply tire is limited to a

FIGURE 18-3 Static steel wheel roller.

FIGURE 18-4 Pneumatic tire roller.

tire pressure of 400 kPa (60 psi), whereas a 10-ply tire can carry a pressure of up to 600 kPa (90 psi). A 12-ply tire, normally used on most large pneumatic tire rollers, can be inflated up to 800 kPa (120 psi) to compact asphalt mixes. The minimum weight of the pneumatic tire roller should be 13.6 tonnes (15 tons).

If the mix is tender, use of a lower tire pressure will displace the mix less than will use of a higher pressure. For a stiff mix, a higher tire pressure can be used because the mix will be stable enough to support the weight of the roller without shoving laterally under the tires. Tire pressure is normally kept constant for a given project, but the level selected should be dependent on the properties of the mix being compacted and the position of the roller on the mat. Tire pressure should not necessarily be the same if the pneumatic tire roller is used in the breakdown position as if used in the intermediate position. Higher tire pressure can often be employed when the pneumatic tire roller is used in the intermediate position because the mix should be stiffer at the lower temperatures in this stage of the process and can thus support more compactive effort without distortion.

The tires on the pneumatic roller will pick up the mix if the roller moves into the mix when the tires are cold. The tires will also often pick up the mix when an oversanded surface course mix is being compacted. Pickup may be a significant problem as well when the mix has been modified with polymer additives. If the mix contains a rubber additive, the pickup problem may be so severe that this type of roller cannot be used. If pickup of the mix on the tires is found to be a major problem, it should be determined whether the mix contains a modified binder material, although if the asphalt cement has been formulated to meet a PG binder grade, the binder supplier may be unwilling to reveal its composition for proprietary reasons.

Attempts are frequently made to eliminate the pickup problem by spraying water or a release agent on the tires during the rolling process. This practice does not always solve the problem. If the roller is not damaging the mat, a better solution is to allow the tires on the roller to reach the same temperature as the mix being compacted without spraying water or release agent on the tires. Pickup will be minimized or eliminated. Skirts consisting of pieces of plywood or rubber sheeting, shown in Figure 18-5, are sometimes hung from the sides of the roller around the tires to shield the tires from the wind and prevent them from cooling off. This approach is effective, especially on windy, cool days.

If a pneumatic tire roller is to be used as the breakdown roller in the roller train at the start of paving in the morning, it is suggested that to minimize pickup, the roller be run back and forth for 10 to 15 minutes on the cold pavement before the paver begins to lay mix in order to start building up heat in the tires. Once paving begins, the roller should be operated in the intermediate position, behind a static steel wheel or vibratory roller, for another 10 minutes while the temperature of the tires increases to the same level as that of the mix. No water or release agent should be applied to the tires during this warmup time.

FIGURE 18-5 Pneumatic tire roller with skirts.

During the heating process, some pickup of the mix on the tires may occur. Once the tires have reached the same temperature as the mix, however, the amount of pickup will decrease. At this time, the roller should be briefly moved off of the paving lane, the tires quickly cleaned off, and the roller moved back onto the hot mix. The pneumatic tire roller can then be moved into the breakdown position and should be able to operate successfully without pickup of the mix. If the paving process is interrupted for any significant length of time, however, this preheating startup procedure will have to be repeated. In no case should the pneumatic tire roller be parked on the hot mat in an attempt to keep the tires warm while waiting for the paving operation to restart.

Once the size of the pneumatic tire roller and the tire pressure to be used have been selected, the only variables that can be controlled easily by the operator are the rolling speed, the location of the roller with respect to the paver, and the number of roller passes over each point in the pavement surface. If the compactive effort applied by the pneumatic tire roller is not adequate, the operator should alter the wheel load on the tires or change the inflation pressure, or both.

Vibratory Rollers

Vibratory rollers (see Figure 18-6) come in a variety of configurations. Single-drum vibratory rollers are manufactured with both a rigid and an articulated frame. Double-drum vibratory rollers come with rigid, single-articulated, and double-articulated frames. These rollers can be operated in any of three modes: static (with the vibrators off), with one drum vibrating and one drum static, and with both drums vibrating.

Vibratory rollers apply two types of compactive effort to the HMA—static weight and dynamic (impact) force. The compactive effort derived from the static weight of the roller is caused by the weight of the drums and frame. The compactive effort derived from the dynamic force is produced by a rotating eccentric weight located inside the drum (or drums). As the eccentric weight rotates about the shaft inside the drum, a dynamic force is produced. This force is proportional to the eccentric moment of the rotating weights and the speed of rotation. Changing the eccentric moment arm or adjusting the eccentric mass has a directly proportional effect on the dynamic force.

Although it is possible to combine the static weight and dynamic force to determine a total applied force, this procedure is not recommended for comparing vibratory rollers of the same or different classes. Rather, components of the total applied force should be evaluated separately. The elements of comparison for the dynamic component of a vibratory roller are the magnitude of the centrifugal force, its vibrating frequency, the nominal amplitude, and the ratio of the vibrating and nonvibrating masses acting on the drum. Nominal amplitude is defined as the weight of the drum divided by the eccentric moment of the rotating weight and is a function of the weight of the drum and the location of the eccentrics.

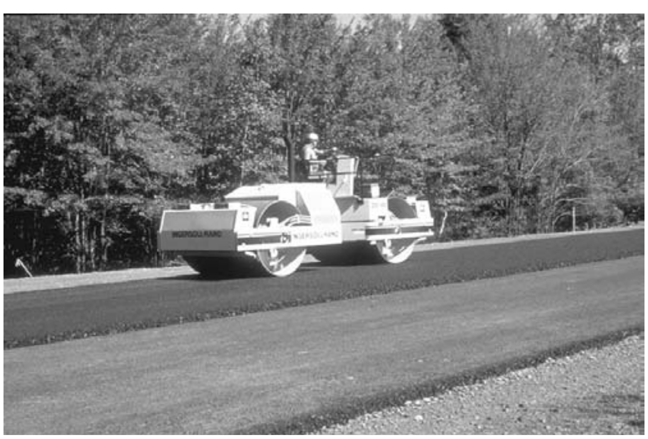

FIGURE 18-6 Vibratory steel wheel roller.

Normal values of nominal amplitude range from 0.25 to 1.02 mm (0.01 to 0.04 in.). Some rollers can operate at only one fixed amplitude. Others have high and low amplitude positions. For these rollers, the low nominal setting is typically 50 percent of the high setting. On some vibratory rollers, several (up to eight) different amplitude settings can be selected. The actual amplitude differs from the nominal amplitude because of the variation in the damping effect of different materials at different states of compaction. An increase in the applied nominal amplitude of vibration increases the compactive effort applied to the asphalt mixture. For a given frequency, changing the amplitude setting has a proportional effect on the dynamic force. For a given amplitude, changing the frequency influences the dynamic force to the second power.

The effectiveness of an increase in the amplitude value, however, is sometimes dependent on the thickness of the layer being densified. For relatively thin layers of mix, generally less than approximately 30 mm ($1\frac{1}{4}$ in.) in compacted thickness, the vibratory roller should typically be operated in the static mode—without vibration. Otherwise, as the mix densifies under the applied compactive effort of the vibratory roller, the drums will begin to bounce. This in turn may cause the mix to shove and decompact instead of densifying, depending in part on the stiffness of the underlying pavement structure. In addition, when the roller is operated in the vibratory mode on a thin lift, some of the aggregate in the HMA will be crushed.

In general, for layers with a thickness of 30 mm ($1\frac{1}{4}$ in.) or more, a low amplitude setting should be used on the vibratory roller. This setting should be maintained unless the compacted thickness of the layer is at least 65 mm ($2\frac{1}{2}$ in.). As the thickness of the layer increases beyond this level, the amplitude setting on the roller can generally be raised to increase the compactive effort applied to the mix. It should be noted, however, that very few layers of HMA are more than 65 mm ($2\frac{1}{2}$ in.) in compacted thickness.

If there is a problem in achieving density quickly, roller operators will sometimes raise the amplitude setting on the roller. This is not necessarily the correct practice. In most cases, particularly for lifts 65 mm ($2\frac{1}{2}$ in.) or less, increasing the applied force may cause the aggregate in the mix to fracture and actually reduce rather than increase density. Better practice is to increase the number of passes made over the mix with the vibratory roller operated at the low amplitude setting. The vibratory roller should be operated at low amplitude unless high amplitude is needed to achieve a particular density level. If so, the mix should be stiff and internally stable enough to support the added compactive effort without checking of the mix or fracturing of the aggregate.

Vibration frequency is the number of complete rotations per minute of the eccentrics: the faster the rotation, the greater the frequency. Some vibratory rollers can operate at only one frequency; others have a choice of two or more frequency settings. Most older vibratory rollers can operate with frequencies in the range of 1,600 to 2,400 vibrations per minute, whereas newer rollers can operate at up to 3,600 vibrations per minute. In general, to apply adequate compactive effort to the HMA without introducing ripples or roughness into the surface of the layer, a vibratory roller should be operated at a frequency of at least 2,000 vibrations per minute. Further, with few exceptions, the vibratory roller should be operated at as high a frequency setting as possible.

Spacing of the impacts depends on the frequency of the vibration and the travel speed of the roller. As frequency decreases and roller speed increases, the distance between impacts on the surface of the mix increases. Conversely, an increase in the vibratory frequency and a decrease in the roller speed both cause the number of impacts per foot of distance to increase, thereby increasing the compactive effort applied by the roller. A smaller impact spacing (a greater number of impacts per foot) is usually preferred. It must be realized, however, that the productivity of the roller can decrease as the roller speed is reduced.

Several roller manufacturers suggest that the ideal impact spacing is in the range of 30 to 40 impacts per meter (10 to 12 impacts per foot) in order to provide a balance between roller productivity and layer smoothness. This spacing can be determined by dividing the roller speed by the frequency of vibration: impact spacing = roller speed in meters (feet) per minute, divided by frequency of vibrations. An applied force of 30 impacts per meter is equal to approximately 33 mm between impacts, whereas 40 impacts per meter is equal to 25 mm between impacts (an applied force of 10 impacts per foot is equal to 1.2 in. between impacts, while 12 impacts per foot is equal to 1.0 in. between impacts).

At a frequency of 2,400 vibrations per minute, a roller speed of about 4.8 km/h (80 m/min) will result in an impact spacing of 33 mm (30 impacts per meter), and a roller speed of about 3.6 km/h (60 m/min) will result in an impact spacing of 25 mm (40 impacts per meter) (at a vibratory frequency of 2,400 vibrations per minute, a roller speed of approximately 2.7 mph will result in an impact spacing of 10 impacts per foot, and a roller speed of about 2.3 mph will result in an impact spacing of 12 impacts per foot). If the vibratory frequency is set at 3,000 vibrations per minute, the corresponding roller speeds will be approximately 5.6 and 4.2 km/h for impact spacings of 30 and 40 impacts per meter, respectively (if the vibratory frequency is set at 3,000 vibrations per minute, the corresponding roller speeds will be about 3.4 and 2.8 mph for an impact spacing of 10 and 12 impacts per foot, respectively).

As noted, the vibratory roller should generally be operated at as high a frequency as possible. A roller capable of 2,000 to 2,400 vibrations per minute, for example, should be operated at the upper end of this frequency range. Using the highest possible frequency of vibration increases the number of impacts per meter (foot) at a given roller speed. For the vast majority of paving projects encountered, the properties of the HMA will not affect the selection of the frequency setting, nor will the thickness of the layer being compacted, as long as the thickness is greater than 25 mm (1 in.). Most vibratory rollers are designed so that the highest frequency can be used at the highest amplitude setting, although for some rollers, it is necessary to operate at a somewhat lower frequency when the roller is used at the highest amplitude setting. The optimum combination of vibratory amplitude, vibratory frequency, and roller speed will provide for the greatest gain in density for each pass of the roller and also the greatest smoothness for the pavement surface.

When using a vibratory roller, the operator is in control of more variables than when using the other types of rollers and thus should be well versed in the proper selection and interaction of those variables. Nominal amplitude and frequency can be varied in addition to the roller speed, the location of the roller with respect to the paver, and the number of passes made over each point on the pavement surface.

For double-drum vibratory rollers, the operator can vibrate either one or both drums. Thus the operator can control the compactive effort applied to the mix to a greater degree than is possible with either static steel wheel or pneumatic tire rollers. In most cases, it is most efficient to operate both drums of a double-drum vibratory roller in the vibratory mode. The only exception is when the roller is moving up or down a steep hill, in which case it may be necessary to run only one drum in the vibratory mode so the roller can maintain forward motion on the hill without sliding off the mat.

Some roller operators run in the vibratory mode while moving only in one direction behind the paver—usually toward the paver. When the roller is moving away from the paver, the operator switches off the vibration and runs in the static mode. For the vast majority of HMA mixes, there is no reason to operate the roller in the static mode and reduce the compactive effort of this type of roller.

Construction of a roller test strip may be necessary to determine the optimum combination of roller speed and vibratory amplitude for a particular set of project conditions. If the required density cannot be achieved, the speed of the roller typically should be decreased and the nominal amplitude setting changed, unless the roller is already at the lowest amplitude setting.

Care should be taken when a vibratory roller is operated in the vibratory mode if underground utilities or drainage structures are directly beneath the pavement layer being compacted. If there is any chance that those utilities or structures might be damaged by the vibrations from the roller, the equipment should be operated in the static mode.

Combination Rollers

Combination rollers combine a vibratory roller drum on the front of the roller and a set of four rubber tires on the back. It has been suggested that these rollers are the best of both worlds since they combine two distinctly different types of compactive effort—vibratory force and pneumatic tire kneading action. In reality, however, this type of roller may produce a significant variation in density across the width of the lane being compacted.

The outside width of the rubber tires is generally equal to the width of the vibratory drum. The problem is, however, the gaps between the four rubber tires on the back of the roller. Unlike a standard pneumatic tire roller in which the tires on the back of the roller fit into the spaces left by the gaps between the front tires, the combination roller has no extra tires to fill in the gaps. It would be unrealistic to expect the roller operator to be able to overlap each succeeding pass of the roller by exactly one tire width to obtain uniform density across the entire lane width. This type of roller should therefore be used with caution when compacting HMA.

COMPACTION VARIABLES UNDER OPERATOR CONTROL

For all types of rollers, the primary compaction variables that can be controlled during the rolling process are roller speed, number of roller passes, rolling zone, and rolling pattern. For vibratory rollers, direction of travel and mode of operation are also under the operator's control. Each of these factors has an effect on the level of density achieved under the compactive effort applied to the mix.

Roller Speed

The more quickly a roller passes over a particular point in the new asphalt surface, the less time the weight of the roller "dwells" on that point. This in turn means that less compactive effort is applied to the mixture. As roller speed increases, the amount of density gain achieved with each roller pass decreases. The roller speed selected is dependent on a combination of factors: paver speed, layer thickness, and position of the equipment in the roller train.

Static steel wheel rollers can operate at speeds of 3 to 9 km/h (2 to 5 mph); pneumatic tire rollers typically run at 3 to 11 km/h (2 to 7 mph); and vibratory rollers can operate at speeds of 3 to 6 km/h (2 to 3½ mph). In the breakdown position, each type of roller should be operated at the lower end of its speed range. In the intermediate position, the speed of the roller can be increased somewhat, typically to the middle of the speed range. In the finish rolling position, the roller can be near the upper end of its speed range. Table 18-1 shows the range of roller speeds for three different types of rollers and three different operating positions. Rollers can move more quickly or more slowly than these speeds, but compactive effort is significantly improved at slower roller speeds.

Roller speed is also governed by the lateral displacement or tenderness of the asphalt mix. If the mixture moves excessively under the rollers, the speed of the compaction equipment should be reduced. In addition, roller speed affects the impact spacing for vibratory rollers. As discussed earlier, this spacing is important for controlling the amount of dynamic compaction energy applied to the mix, as well as for obtaining the proper surface smoothness.

Roller speed is usually established by the speed of the paver. Too often if the paver pulls away from the rollers, the rollers increase speed to catch up, which causes density in the asphalt mixture to be lower after applying the same number of roller passes. Paver speed should be selected to match the production rate of the asphalt plant, and that speed should be kept constant. The speed for each roller should then be determined based on the paver speed and the number of passes each roller must apply.

TABLE 18-1 Range of Roller Speeds (mph)

	Operating Position		
Type of Roller	**Breakdown**	**Intermediate**	**Finish**
Static steel wheel	2–3½	2½–4	3–5
Pneumatic	2–3½	2½–4	4–7
Vibratory	2–3	2½–3½	—

Note: 1 mph = 1.6 km/h.

Changing roller speed merely causes variations in density. "Slow and steady" is the key to proper compaction.

If the paver continually pulls ahead of the rollers, several courses of action can be taken. First, paver speed can be reduced to match both plant and roller production. Too often the paver is operated on a "hurry and wait" basis between truckloads. If plant production capacity necessitates continued higher paver speeds, additional rollers are required to achieve adequate density. Wider rollers can also be employed. For example, a vibratory roller 2.1 m (7 ft) wide can be used in place of a tandem roller 1.4 m (4½ ft) wide. The type of roller used can be changed as well; for example, a double-drum vibratory roller can be used instead of a single-drum vibratory or static steel wheel roller.

The breakdown roller and sometimes the intermediate roller may stop whenever the paver stops to wait for trucks, even though the rollers have not completed their roller patterns. When the next truck arrives and the paver again starts moving, the rollers also restart and finish compacting the mix. While the rollers have been idle, however, the mix on the roadway has cooled, and the density obtained in the cooled area will usually be less than that in the surrounding area. The roller should keep rolling until the established pattern and number of passes over each point have been completed.

Number of Roller Passes

To obtain the target air void content and uniform density in an asphalt mixture, each point in the pavement must be rolled a certain number of times. The number of required passes depends on many variables, including, most important, the type of compaction equipment. Three-wheel steel wheel rollers, tandem steel wheel rollers, pneumatic tire rollers, and single- or double-drum vibratory rollers all have different capabilities. At the same time, the capabilities of each type of roller depend on mat thickness, mix temperature, mix design properties (binder content, binder stiffness, and aggregate characteristics), and environmental conditions. Finally, the number of passes required depends on the position of the roller in the roller train.

One or more test strips should be constructed at the start of any major paving project to determine the minimum number of roller passes needed to achieve proper density levels. Different combinations of rollers and roller patterns should be tried to determine the optimum combination of compaction variables that will achieve the required density level as efficiently as possible. Rarely will the first trial combination of rollers, roller passes, and rolling zones provide the most economical rolling sequence, unless the mix is one the contractor has used many times in the past.

Roller passes must be distributed uniformly over the width and length of the mat. All too often the center of the paver lane (the area between wheelpaths of a single-lane pavement) receives adequate roller coverage, whereas the edges of the mat receive considerably less compactive effort. As discussed further below in the section on rolling patterns, the uniformity of roller passes across the lane width is just as important as the number of passes.

Rolling Zone

Compaction must be achieved while the viscosity of the asphalt binder in the mix and the stiffness of the mix are low enough to allow for reorientation of the aggregate particles under the action of the rollers. In other words, the mat must still be hot enough for effective compaction. As discussed earlier, the rule of thumb commonly used is that the proper level of air voids should be obtained before the mix cools from its laydown temperature to 80°C (175°F).

To obtain the required density level most quickly, initial compaction should occur directly behind the laydown machine. If the asphalt mixture is stable enough, breakdown rolling can be carried out very close to the paver, while the mat temperature is still high. More density is obtained with one pass when the mix temperature is 120°C (250°F) than when it is 110°C (230°F). Thus the front of the rolling zone should be as close as possible to the back of the paver.

Sometimes when a tender mix is placed, initial rolling is delayed to avoid excessive shoving or checking of the mix by the rollers. Depending on mix characteristics, the required density can be achieved as long as the proper combination of rollers and compactive effort is applied. In some cases, however, the mix is so tender that rolling must be delayed to the point that the desired density level cannot be achieved. In this case, other solutions must be tried. When a tender mix is encountered, the cause of the tenderness must be determined and changes made in the mix production and paving operation to ensure adequate density. Compaction of tender mixes is discussed later in this section.

Rolling Pattern

Rollers should be operating most of the time. The question is whether they are operating correctly and effectively. Compaction is frequently not applied in the right place. Numerous compaction studies have shown that the middle of the width of the paver pass typically receives much more compactive effort than the edges. Unfortunately, traffic uses the wheelpath areas near the edge of the pavement more often than the center of a lane.

For example, on an actual HMA paving project on an Interstate roadway, the mixture was placed in a trench section 3.7 m (12 ft) wide in two compacted lifts 75 mm (3 in.) thick. Initial or breakdown rolling on the first layer was accomplished using a vibratory roller 2.1 m (7 ft) wide. For the 3.7-m (12-ft) wide paver pass, two passes of the vibratory roller could cover the whole mat width, with about a 0.5-m (2-ft) overlap in the center. To gain adequate density, the operator of the breakdown roller had to keep the vibratory roller tight to each side of the trench. To cover the complete width of the lane, the operator would need only to make a roller pass on each side of the lane directly toward and then away from the paver without ever attempting to roll the center of the lane.

Instead, the roller operator made his first pass, 3.7 m (7 ft) wide, up the left-hand side of the mat. Upon reaching the back of the paver, the operator reversed direction, changed lateral direction slightly, and moved away from the paver by traveling down the center of the mat, with 0.8 m (2½ ft) of free area on each side of the roller. The third pass, again toward the paver, was along the right-hand edge of the driving lane. The fourth pass (away from the paver) was once more down the center, similar to the second pass. The final pass, to catch up to the paver, was a reversal of the fourth—up the center of the lane. The roller operator continued to repeat this five-pass pattern as the paver moved down the roadway.

Five passes of this breakdown roller were applied to the center of the 3.7-m (12-ft) wide area, an area not used by traffic. Only one pass was applied over each wheelpath and each outside edge of the lift. The roller was simply not being used properly. A future failure was built into this pavement structure because proper density was not obtained in the wheelpaths where it was needed. If the number of roller passes made on each edge of the lane being compacted is adequate to meet specifications, the density level in the center of the lane will always be more than enough to also meet specifications. Thus roller patterns should be designed to ensure proper, uniform compaction of the entire lane width.

For each roller used on a project, the mat width can be divided by the width of the compaction drums to determine the number of passes needed to cover each transverse point in the surface. A pass is defined as one trip of the roller in one direction over any one spot. Multiple passes are needed to completely compact each point in the pavement surface over the transverse width of the lane being paved to the required level of density.

If the width of the roller drums (or tires) is 2.1 m (7 ft), only two passes are needed to cover a lane 3.7 m (12 ft) wide, including an overhang 150 mm (6 in.) wide over each edge of the pavement. Two passes of the 2.1-m (7-ft) wide roller overlap for a distance of about 300 mm (12 in.) in the center of the lane. If allowance is made for the fact that the roller operator may not always be able to maintain a 150-mm (6-in.) overhang on the edge of the pavement, the 300-mm (12-in.) wide overlap in the center of the lane is still sufficient to permit the entire pavement width to be compacted in two passes with a minimum 150-mm (6-in.) wide overlap needed between roller passes.

A roller that is 1.8 m (6 ft) wide cannot cover a complete 3.7-m (12-ft) lane width in only two passes. Two passes do not allow for any overhang at the edge of the lane or any overlap at the center. Thus three passes of a 1.8-m (6-ft) wide roller are necessary to compact the lane properly.

If the roller has drums or tires that are only 1.5 m (5 ft) wide, three passes of the roller are required, as with a roller with 1.8-m (6-ft) wide drums. If 150 mm (6 in.) is allowed for the edge-of-lane overhang, the amount of overlap between roller passes should be about 300 mm (12 in.). This overlap allows for ample steering variation by the roller operator and permits a 3.7-m (12-ft) lane width to be covered with three passes of the 1.5-m (5-ft) wide roller.

A roller with drums 1.4 m (4.5 ft) wide needs to make four passes across the width of a 3.7-m (12-ft) lane to completely cover the lane width. If this roller overhangs each edge of the pavement by 150 mm (6 in.) and only three passes across the lane width are made, the roller drums will overlap only 75 mm (3 in.) between the first and second passes and 75 mm (3 in.) between the second and third passes across the width. This amount of overlap between passes is not adequate to ensure uniform compaction. Thus four passes of the 1.4-m (4.5-ft) wide roller are necessary to properly compact a paving lane 3.7 m (12 ft) wide.

In a longitudinal direction, the rollers should not stop at the same transverse end point with each pass of the roller; the reversal points should be staggered to prevent shoving of the mix. A slight change in direction, or curl, may be beneficial at each reversal spot to further reduce the tendency of the mix to shove under the compactor and to eliminate the possibility of a bump at the point where the roller reversal occurs. The roller should not sit and wait while parked on the hot mat. A long delay caused by a lack of haul trucks at the paver or filling of the compactor with water allows the roller to indent the new mat. It is generally impossible to roll out these marks once the mat has cooled. Thus when idle, all rollers should be parked on the shoulder or at an angle back on the cooler mat.

Many old compaction specifications require the compaction process to start at the low side of the pavement lane and proceed toward the high or upper side on subsequent passes of the roller. With modern compaction equipment and more stable asphalt mixes, this requirement is usually unnecessary, but it may be advisable for superelevations and lifts that are thick in relation to maximum particle size. In addition, some older specifications stated that the rollers had to overlap the width of the previous pass by at least half the width of the roller. This procedure leads to nonuniform compaction across the width of the pavement lane and a distinct lack of density on the outside edges of the lane. Modern standard practice is to have each roller overlap its own pass by a minimum of 150 mm (6 in.).

Determination of the rolling pattern is discussed in detail in the next section.

Direction of Travel and Mode of Operation for Vibratory Rollers

When using a single-drum vibratory roller, the compression drum should normally be operated toward the paver. This practice ensures that the maximum compactive effort of the compression drum is placed on the mat before the lesser compactive effort of the steering drum. In addition, this practice results in a denser layer to better resist displacement of the mix caused by the continual movement of the tiller drum during the steering action. A single-drum articulated-frame roller should also be operated with the driven drum toward the laydown machine, again to ensure that the maximum compactive effort is applied to the mix as quickly as possible.

When only one drum of a double-drum roller is operated in vibrating mode, the roller is often operated with the vibrating drum toward the laydown machine and the static drum trailing. A double-drum articulated-frame roller that has two driven drums (a vibratory tandem roller) operates the same in either direction. Thus for this type of roller, the direction of travel is not a consideration.

For harsh or stiff mixtures, breakdown rolling is normally accomplished with both drums of a double-drum roller vibrating. Subsequent passes are made in the full vibratory mode as well. For mixtures with normal stability, breakdown rolling with a vibratory roller should also generally be accomplished in the full vibratory mode. For tender mixtures, as discussed below, initial breakdown rolling is sometimes accomplished in the static mode or in a combination mode. Subsequent passes are usually made in the combination mode if mixture displacement is not too great. When operating in the combination mode for tender mixtures, the trailing drum instead of the front drum is usually vibrated.

DETERMINATION OF ROLLING PATTERN

Different mixes may require considerably different levels of compactive effort and thus different compaction equipment and rolling procedures. Different types or combinations of rollers may be needed to achieve a required level of density for an asphalt mix containing large aggregate, for example, than for a mix made with smaller-size coarse aggregate.

As suggested earlier, the rolling pattern to be used on a particular paving project should be determined at the start of the project through the construction of one or more roller test strips. The strip(s) should be located at a convenient point where the pavement layer placed will remain as part of the final pavement structure. The mix should be representative of the material to be produced for the project; generally the plant should produce mix for a short period of time before the mix for the compaction test section is made so the mix will be as consistent as possible. The thickness of the layer compacted should be the same as that to be used for the rest of that layer, and the length of the test strip(s) should be at least 100 m (330 ft). The condition of the underlying layers should be representative of that on the rest of the project.

Due consideration should be given to the selection of the rollers to be used. The combination of rollers used on a previous project might not be the most cost-efficient or effective for the variables involved in the present job. Although vibratory rollers are generally used for breakdown rolling and pneumatic tire rollers for intermediate rolling, a greater degree of density with fewer roller passes may be obtained for some stiff mixes when a large pneumatic tire roller is used in the breakdown position, with the vibratory roller following in the intermediate position.

If a large pneumatic tire roller is used in the breakdown position, it is generally difficult to determine the degree of density obtained in the mat by using a nuclear gauge (discussed below) because of the uneven surface of the mat after the first several passes of the pneumatic tires. Nuclear readings must be taken after the mix has been smoothed out with the intermediate steel wheel roller, either vibratory or static. A compaction test strip should be used to determine the most effective sequence of rollers to achieve the required degree of compaction, smoothness of the mat, and economical production.

Desired density levels are easier to obtain when the asphalt mix is hot. As discussed earlier, instead of using the rollers in the traditional roller train formation, consideration should be given to using two breakdown rollers, preferably of the same type, instead of a breakdown roller followed by an intermediate roller. This practice is particularly beneficial on thin layers of mix under unfavorable environmental conditions.

As noted earlier, two breakdown rollers can be operated side by side to expedite rolling. Depending on the width of each roller and the width of the lane, complete compaction across the paving width can normally be accomplished very quickly. If two different rollers are employed side by side in the breakdown position—a double-drum vibratory roller and a pneumatic tire roller, for example—it is important that each roller cover the whole width of the lane at some point during the compaction process. The two rollers will have to leapfrog each other for this to be accomplished, but with a little practice, the operation can be done easily. Again, the purpose of using two rollers, both running in the breakdown position, is to apply compactive effort to the mat before it cools.

Calculation of Rolling Pattern

To determine the optimum rolling pattern, the first calculation needed is the paver speed, which is based on the amount of mix to be produced by the plant, the width of the pavement lane, and the depth of the mix. Once the average paver speed is known, the maximum speed of the rollers should be selected. The speed selected for each roller will depend on the type of roller and its width, as well as its position in the rolling sequence. The selected speed will also depend on the ability of the roller to strike a balance among achieving density, smoothness, and a uniform pavement surface.

The second calculation involves comparing the width of the layer being placed and the width of the rollers to be used in order to determine the number of transverse roller lanes needed to cover the entire width of the pavement. The number of passes must be matched to the speed of the paver. (A pass is defined as a trip of the roller in one direction over any point on the pavement surface.) Given the paver speed, the roller speed, and the number of transverse lanes needed to obtain full-width coverage of the roadway surface, it is possible to determine the number of passes each roller can make over each point in the pavement while still keeping up with the paver.

As discussed earlier, the number of roller passes needed over each point on the pavement surface depends on a large number of variables. One of the most important of these is the level of density required in the pavement layer. If a method specification is being used, the required number of passes can simply be counted. What is not known, however, is the degree of density (air void content) that will be obtained in the mix after the specified number of passes has been completed. If a certain percentage of laboratory density or theoretical maximum density is required, the higher is the required percentage, the more compactive effort will have to be applied to the pavement layer.

The type of breakdown roller used will also be very important. Under some conditions, one vibratory roller may be sufficient to achieve the required density, depending on the properties of the mix. In other cases, say, if the mix is tender and checking occurs, several passes of a pneumatic tire roller may be necessary to achieve the required density level. One or more passes of a static steel wheel roller are normally needed to remove roller marks, particularly if a pneumatic tire roller has been used. Because of the number of variables involved, it is impossible to generalize about the best combination of rolling and roller pattern to use in all cases.

Some contractors always use the same rollers in the same order making the same number of passes over the mix, regardless of the project variables. The same overall compactive effort is applied to a thin lift as to a thick lift, to a mix placed during hot summer months as to one placed during the cool spring or fall season, to a mix placed on top of a very strong foundation and to one placed on top of a weak base, and to a mix that is very stiff and one that is tender. As noted, however, different mixes and different project conditions require different compactive efforts to obtain the same degree of density.

Monitoring Density

The most common method of monitoring changes in density with roller passes is with a nuclear density gauge, shown in Figures 18-7 and 18-8. Density is estimated by transmitting gamma rays into the mix and measuring the amount of radiation reflected back to the device in a given amount of time. The data obtained can be related to the relative density of the layer. Nuclear gauge readings should be taken after each pass of each roller, and the rate of increase in density after each pass determined. When no appreciable increase in density is obtained with

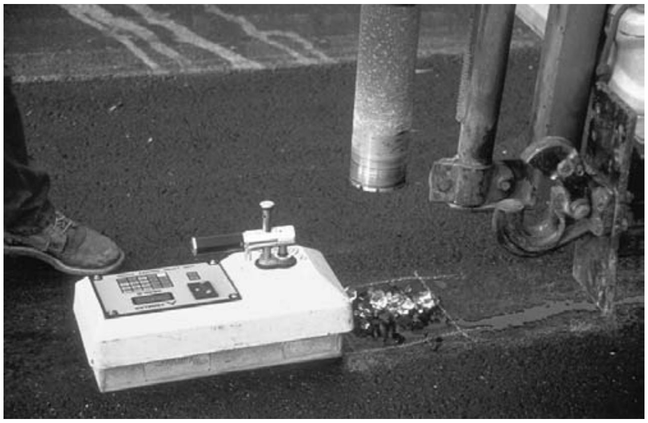

FIGURE 18-7 Nuclear gauge for monitoring density.

the application of additional roller passes, the maximum relative density for that mix has usually been obtained. As noted above, when a pneumatic tire roller is used in the compaction process, particularly in the breakdown mode, it is often very difficult to obtain an accurate density reading with a nuclear gauge. One or more passes with a steel wheel roller may be necessary before a valid nuclear gauge reading can be obtained.

The density value determined with a nuclear gauge is relative and is generally not the same as the density value obtained from cores cut from the pavement. A correlation must be made between the nuclear density reading and the actual unit weight of the pavement using cores that are cut from the test section after the rolling process has been completed. The actual unit weight must be compared with the maximum theoretical unit weight of the mix or the laboratory chemistry to determine whether the required density was achieved.

Because different nuclear gauges provide different readings, a single gauge should be used throughout the project. If more than one gauge is used, each should be

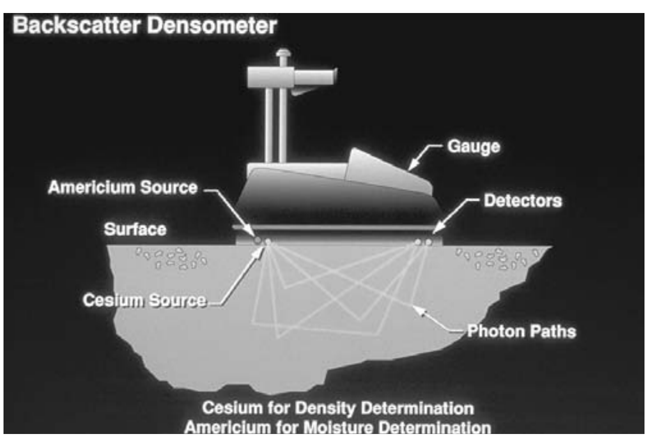

FIGURE 18-8 Schematic of nuclear gauge.

properly correlated to the core density so that the nuclear readings from each will accurately monitor the level of density being obtained in the mat. A new correlation relationship should be developed each time there is a significant change in the design of the HMA mix, the thickness of the layer being compacted, or the stiffness of the underlying pavement structure.

Usually a nuclear density gauge is correlated to unit weight by extracting cores from one of the test strips at the start of the project. A number of locations—10 locations are commonly used—are selected by random number. Multiple density readings are taken on top of each marked spot. Cores are then cut and tested to determine density. A graph is made, with the average nuclear density reading at each location plotted on one axis and the corresponding core density plotted on the other. A best-fit correlation line is drawn through the data points. Later, when the nuclear gauge is used to monitor density, the gauge reading is converted to a core density using the best-fit line.

To obtain a correlation, some operators calculate the average nuclear density reading and compare it with the average core density. In effect, they assume that there is a constant difference between the two methods. In fact, the difference is not constant but depends on the nuclear gauge reading. Therefore, a constant offset should not be used.

Compaction of Stiff Mixes

HMA mixtures that are properly designed will be reasonably stiff and stable and will require a considerable amount of compactive effort to attain the required degree of density. This type of mix will support the weight of the compaction equipment directly behind the paver. If the mix is placed at a temperature of 135°C (275°F) or higher, the rollers will typically be able to compact the mix properly before it cools to a temperature of 80°C (175°F).

Most often, three rollers are used—a breakdown roller, an intermediate roller, and a finish roller. For breakdown rolling, as discussed above, a vibratory steel wheel roller is most often used. For intermediate rolling, a pneumatic tire roller is generally employed, although sometimes a second vibratory roller is used. Finish rolling is normally done with a static steel wheel roller.

The breakdown and intermediate rollers should stay close to the paver. If the mix is stable, a bow wave will not occur in front of the vibratory roller drum, and the mix will not exhibit any cracking or checking. With a relatively stiff mix, the finish roller should also be close to the paver since there will be minimal marks from the breakdown and intermediate rollers to be removed.

For very stiff mixes or when a high degree of density is desired, a pneumatic tire roller should be used for breakdown rolling. For intermediate rolling, a vibratory steel wheel roller should follow directly behind the pneumatic tire roller, and the finish rolling should be done with a static steel wheel roller. Because of the internal stability and strength of the stiff mix, more compactive effort may be needed to obtain a given level of density (percent of theoretical maximum density), but the mix will not move under the compaction equipment during the rolling process.

Compaction of Tender Mixes

A tender mix is generally an internally unstable mix that will not properly support the weight of the compaction equipment when hot and will move under the applied compactive effort. The movement of the mix can take various forms. First, a bow wave may occur in front of the steel wheel on both a vibratory and static steel wheel roller as these rollers move longitudinally up and down the mat. Second, the mat may widen out when the rollers are used to compact the unsupported edge of the lane—mix placed 3.7 m (12 ft) wide, for example, may squeeze out to a width of 3.9 m (12½ ft) or more. Third, checking—short, transverse cracks that develop during the compaction process—may occur in the mix. Fourth, longitudinal humping up and checking of the mix may occur immediately outside of the edges of the steel wheel on the rollers.

Tenderness usually comes in one of two forms. Classical tenderness occurs when the breakdown roller is unable to approach the paver without the mixture beginning to move. Mid–temperature range tenderness occurs when the mixture behind the paver will support the roller but begins to move when the mixture starts to cool off.

When classical tenderness is encountered, roller operators do not approach the back of the paver. They trail some distance behind the paver waiting for the mixture to cool sufficiently until the roller is supported. The main approach to handling classical tenderness is to allow the mixture to cool. The best method is to redesign the mixture. If the mixture is used on a high-traffic route, the mix should be redesigned because classical tenderness is usually a sign of a non-rut-resistant mixture.

When mid–temperature range tenderness is encountered, the rollers can approach right up to the paver. The characteristics of mid–temperature range tenderness normally show up under breakdown rolling if the temperature of the mix at that point is above approximately 115°C (240°F). Whether the initial rolling is completed by a vibratory or pneumatic tire roller, the mix is generally stable at higher temperatures. When the temperature of the mat drops below this level, however, the mix may become very unstable and tender. A bow wave may be seen in front of the steel wheel rollers, checking may occur in the surface of the mat, and the mix may hump up outside the edges of the steel drums on the rollers. Further, the mix may start to creep out transversely along any unsupported longitudinal edge of the mat.

The mix may continue to exhibit these tenderness characteristics as the temperature of the mat decreases to approximately 90°C (193°F) or lower. If rolling is attempted in this middle temperature range, the mix will decompact instead of compacting. It is not until the mix is quite cool, generally less than 90°C (193°F), that it becomes stiff enough to again support the weight of the compaction equipment. Finish rolling can often be accomplished at temperatures of 70°C (158°F) or less. Further, it is typically difficult for the finish roller to completely remove all of the roller marks left in the mix by the breakdown and intermediate rollers.

It should be noted, however, that the temperatures cited above—115°C (240°F) down to 90°C (193°F)—do not represent exact values. Initial tenderness of the mix may be evident at temperatures as high as 120°C (248°F) or as low as 110°C (230°F), depending on the characteristics of the mix. Further, the mix may continue to exhibit tenderness characteristics at temperatures as high as 95°C (203°F) or as low as 80°C (175°F).

Several different techniques can be used to compact mid-temperature tender mixes to the required level of density. First, tender mixes generally do not become tender until the mix temperature falls. This means a significant amount of compactive effort can be applied to the mix before it becomes tender and starts to move. If a vibratory roller is used as the breakdown roller, it should be kept as close to the paver as possible. The roller should make as many passes as possible over the mat, as quickly as possible, before the mix begins to move, check, or mark. Once the movement starts, additional passes of the breakdown roller should not be made. For most tender mixes, three to five passes of the breakdown roller can be made over each point in the mat surface before the movement or checking begins.

Second, if the mix is moving under the rollers in the middle temperature range, steel wheel rollers, either vibratory or static, should be kept off the mix until it cools to the point where it is again stable enough to support the weight of the compaction equipment. If rolling is continued when the mat is moving, even more movement will typically occur; the mix will become less stable with the application of additional compactive effort. For some mixes, severe shoving of the mix may occur at the outside edge of a steel wheel roller drum with continued rolling.

In the middle temperature range at which decompaction of a tender mix will occur if steel wheel rolling is carried out, a pneumatic tire roller can be used. The rubber tires on this roller are less likely to shove or check the mix, and a bow wave will not develop. The pneumatic tire roller thus can be used to gain density in the middle temperature range.

The static steel wheel finish roller should be kept well back of the paver. This roller should move up toward the paver, compacting the mix and taking the roller marks out, until the temperature is reached at which the mix begins to move or check under the applied compactive effort. When the checking or bow wave starts, the finish roller should be backed off, and finish compaction should be carried out at lower temperatures.

If a pneumatic tire roller is not available for use once the mix has begun moving and checking, two double-drum vibratory rollers can be used together, in echelon formation or side by side, immediately behind the paver. The use of two rollers will permit more passes of the two breakdown rollers to be made over each point in the mat surface before the mix cools to the temperature at which movement and checking occur. Because each of the two rollers has less surface area to compact, it is often possible to make five to seven passes over each point in the mat before the decompaction process begins. For a tender mix, this is usually sufficient to obtain the required density level. Finish rolling is accomplished only to remove any roller marks, with extreme care taken to roll at a low enough temperature not to disturb the already compacted mix.

Tender Zone

Many contractors have observed a tender zone when using Superpave mixes, referred to earlier as mid-temperature tender mixes. The following comments about the tender zone were taken from National Asphalt Pavement Association *Special Report 180*:

> On some Superpave designed mixtures, a tender zone has been identified in temperature ranges of approximately 200–240°F (93–115°C). The mixture can be satisfactorily compacted above this range or below this range, but the mixture is tender within the temperature range and cannot be adequately compacted. This is not true for all mixtures, but it has been observed for some Superpave designed mixtures. The mixture can be satisfactorily rolled with rubber-tire rollers within this tender range but, as stated earlier, these rollers may have a pick-up problem when modifiers are used. Contact the roller manufacturers regarding procedures for eliminating asphalt pick-up on rubber-tire rollers.
>
> When a mixture is being produced that is tender within the mid-temperature range, the preferred compaction method is to obtain density prior to cooling to the tender zone. This may require an additional breakdown roller or other changes in rolling techniques, but obtaining density prior to reaching the tender zone is preferable. In some cases, the mixture temperature may be increased slightly to provide more compaction time. However, excessive temperatures will magnify the problem. Another alternative is to use a vibratory steel-wheel breakdown roller above the tender zone, followed by a rubber-tire roller which can be operated in the tender zone. The finish roller should be used after the mixture has cooled below the tender zone. This second method may not be satisfactory if the rubber-tire roller picks up excessively.
>
> Another possibility is to breakdown with a steel wheel roller above the tender zone then complete the rolling process after the HMA has cooled to below the tender zone. This has been used on a number of projects, but problems may occur due to differential cooling of the mixture and due to excessive aggregate breakdown when rolling in the vibratory mode after the mixture has cooled to below 200°F. Therefore, vibratory rolling should not be used below approximately 200°F.
>
> If the tenderness problem yields a pavement with poor in-place density, or if the paving train length is excessively long due to the time required for the mixture to cool, adjustments to the mixture design must be made to eliminate, or at least reduce, the temperature tenderness zone. It is important that the paving crew working at the laydown site communicate with plant personnel.

SUMMARY

The following factors should be considered in monitoring the compaction process (the factors that should be considered when monitoring joint construction, as outlined in Section 17, apply here as well):

- To compact an asphalt layer properly, the rollers should be used efficiently while the mix is still above the minimum compaction temperature.
- The time available for compaction is related primarily to the thickness of the layer being placed. An increase in lift thickness can substantially increase the time available for the roller to densify the mix.

■ An increase in the laydown temperature of the mix behind the paver can also increase the amount of time available for compaction. The feasibility of this approach, however, depends on the properties of the asphalt mix at that elevated temperature and the tenderness of the mix under the compaction equipment.

■ A decrease in the speed of the rollers will increase the compactive effort applied to the mix.

■ The breakdown and intermediate rollers should be operated as close to the paver as possible to obtain density before the mix cools to a minimum temperature of 80°C (175°F).

■ If the mix cannot support the weight of the compaction equipment, the mix should be redesigned or the compaction procedures changed.

■ The rolling pattern should be monitored to ensure that the compaction equipment is applying the same amount of compactive effort at all points transversely across the lane being paved.

■ The speed of the compaction equipment will depend on the type of roller being used and its position in the compaction process. For static steel wheel and pneumatic tire rollers in the breakdown position, the maximum speed should not exceed 4.0 km/h (2½ mph). For a vibratory roller in the same position, the maximum speed should not exceed 6 km/h (3½ mph), depending on the frequency of vibrations.

■ A vibratory roller should be operated at the maximum possible vibratory frequency in order to increase the number of impacts per foot. At least 30 to 40 impacts per meter (10 to 12 impacts per foot) are needed to obtain adequate density and layer smoothness.

■ The nominal amplitude setting on the vibratory roller should be determined in accordance with the characteristics of the mix and the thickness of the layer being compacted. In general, vibratory rollers should be operated in the static mode when the compacted lift thickness is less than about 30 mm (1¼ in.). For greater lift thicknesses, the roller should normally be operated at low nominal amplitude. If density cannot be obtained, the nominal amplitude may be increased to determine whether additional compactive effort will be beneficial in achieving the required density level. In general, the nominal amplitude setting can be increased in proportion to the increase in compacted thickness of the layer.

■ The optimum combination of rollers and rolling patterns for a past project may not be the same as that for a current project or even for a different type or layer of mix on the same project. One or more test sections should be constructed to determine the most efficient and effective combination of compaction equipment and rolling patterns to use for each combination of job variables.

■ Two similar rollers run side by side (in echelon) will typically produce a greater level of density in the mix with the same number of roller passes than will result with the same two rollers operated end to end as breakdown and intermediate rollers.

■ If the rollers cannot keep up with the speed of the paver, more rollers should be used, or the paver should be slowed down.

■ A mid-temperature tender zone has been identified for some Superpave mixes. These mixes show tenderness in the approximate temperature range of 95°C to 115°C (200°F to 240°F). Close attention to rolling procedures can minimize this problem.

SECTION

19 Mat Problems

Mat problems can be defined as defects that occur in the asphalt mixture during or soon after the laydown and compaction operations have been completed. These problems fall into two primary categories: (*a*) equipment-related problems and (*b*) mixture-related problems. In this section, major mat problems are reviewed and a description of each problem is presented, including its causes, solutions, and effects on long-term pavement performance.

Table 19-1 summarizes the problems reviewed. The first column lists the various problems, while the remaining columns enumerate possible causes for each. The checks indicate equipment-related causes, while the x's indicate mix-related causes, which should generally be corrected by changes in the mix design. Provided throughout the discussion of causes are cross-references to earlier sections where greater detail can be found. Note that because of the interaction of various equipment-related and mix-related causes, no attempt has been made to rank the various causes.

SURFACE WAVES

Description

An asphalt surface can have two types of waves: short and long. Short waves, also sometimes called ripples or auger shadows, are generally 0.3 to 0.9 m (1 to 3 ft) apart, with 0.45 to 0.60 m (1½ to 2 ft) being the most common separation. Long waves are considerably farther apart. The distance between them may correspond to the distance between truckloads of mix. Long waves may also be associated with the reversal points of the compaction equipment, particularly on thick-lift construction or when the HMA being placed is tender and moving longitudinally under the compaction equipment.

An additional type of defect in the pavement surface is a roughness or washboard effect caused by improper operation of a vibratory roller. The distance between these waves is generally very small, typically less than 75 or 100 mm (3 or 4 in.).

Causes

A major cause of short waves or ripples is a fluctuating head of material in front of the paver screed. The variation in the amount of mix being carried back to the augers by the slat conveyors and deposited in front of the screed causes the screed to rise and fall as the force pushing against it changes. Too much mix (at the top of the augers) and then too little mix (at the bottom of the augers) being carried in the auger chamber in front of the screed causes the wavy surface as the screed reacts to this variation in force. The fluctuating head of material causes the screed to rotate around its pivot point and "hunt" for an angle of attack. As the angle of attack of the screed changes, the thickness of the mat being placed also changes, and the smoothness of the new layer is directly affected. (See Section 15.)

Another cause of short waves is a screed that is in poor mechanical condition—one with excessive play in the screed control connections. Short waves can also be formed in the mat by improper mounting or sensitivity of the automatic grade control on the paver or by use of an inadequate grade reference device. Or the problem may be related to a mobile reference (floating beam) that is bouncing, or to the truck driver's holding the brakes while the truck is being pushed by the paver. (See Section 16.)

Short waves can also be related to the mix design, particularly with a mix that varies in stiffness as a result of changes in the mix temperature or composition. (See Section 3.) As the stiffness of the mix varies, the forces of the mix pushing on the screed vary as well, causing the screed to rise and fall and resulting in a mat with short waves. Finally, if the mix design is improper in aggregate gradation, asphalt content, mix temperature, or moisture content (the mix is tender), the rollers may shove and displace the mix during the compaction process. Normally, however, short waves are placed in the mat by the paver because of either its operation or changes in mix stiffness, rather than by the operation of the compaction equipment.

Long waves are caused by some of the same variables that result in short waves. Fluctuation in the amount of material in front of the screed and variation in mix stiff-

TABLE 19-1 Mat Problems and Their Causes

Causes

Problem	Fluctuating Head of Material	Feeder Screws Overloaded	Finisher Speed Too Fast	Too Much Lead Crown In Screed	Too Little Lead Crown In Screed	Overcorrection of Thickness Control Screws	Excessive Play in Screed Mechanical Connection	Screed Riding on Lift Cylinders	Screed Plates Worn Out or Warped	Screed Plates Not Tight	Cold Screed	Moldboard on Strikeoff Too Low	Running Hopper Empty Between Loads	Feeder Gates Set Incorrectly	Kicker Screws Worn Out or Mounted Incorrectly	Incorrect Nulling of Screed	Screed Starting Blocks Too Short	Screed Extensions Installed Incorrectly	Vibrators Running Too Slow	Grade Control Mounted Incorrectly	Grade Control Hunting (Sensitivity Too High)	Grade Control Wand Bouncing on Reference	Grade Reference Inadequate	Sitting Long Period Between Loads	Improper Joint Overlap	Improper Mat Thickness for Max. Agg. Size	Trucks Bumping Finisher	Truck Holding Brakes	Improper Base Preparation	Improper Rolling Operation	Reversing or Too Rapidly Turning Rollers	Parking of Roller on Hot Mat	Improper Mix Design (Aggregate)	Improper Mix Design (Asphalt)	Mix Segregation	Moisture in Mix	Variation of Mix Temperature	Cold Mix Temperature
Wavy Surface—Short Waves (Ripples)	✓	✓	✓				✓	✓		✓										✓	✓	✓	✓						X	X			X	X	X		X	
Wavy Surface—Long Waves	✓	✓				✓	✓	✓					✓	✓						✓			✓	✓			X	X	X		X	X			X		X	
Tearing of Mat—Full Width			✓						✓		✓															X							X	X	X	X	X	X
Tearing of Mat—Center Streak					✓				✓		✓			✓	✓																							X
Tearing of Mat—Outside Streaks				✓					✓		✓	✓		✓				✓																				X
Mat Texture—Nonuniform	✓	✓	✓					✓	✓	✓	✓		✓					✓	✓					✓		X			X				X	X	X		X	X
Screed Marks							✓																				X	X										
Screed Not Responding to Correction			✓				✓	✓		✓										✓						X											X	X
Auger Shadows		✓																															X	X	X			
Poor Precompaction			✓					✓											✓							X			X									X
Poor Longitudinal Joint	✓	✓				✓		✓												✓	✓	✓			✓					X								X
Poor Transverse Joint		✓					✓	✓		✓						✓	✓													X								X
Transverse Cracking (Checking)																													X	X			X	X		X	X	
Mat Shoving Under Roller																													X	X	X		X	X		X	X	
Bleeding or Fat Spots in Mat																																	X	X		X	X	
Roller Marks																													X	X	X	X					X	
Poor Mix Compaction																													X	X	X	X	X	X		X	X	X

1. Find problem above.
2. Checks indicate causes related to the paver. X's indicate other problems to be investigated.

NOTE: Many times a problem can be caused by more than one item; therefore, it is important that each cause listed be eliminated to ensure that the problem will be solved.

ness cause the screed to react to the change in the force exerted on it. If the distance between the wave peaks corresponds to the length of pavement between truckloads of mix, however, the waves may have been caused by incorrectly set hopper flow gates on the paver or by the paver hopper and slat conveyors being emptied between loads of mix. (See Section 13.) Poor mechanical condition and improper operation of the screed (continually changing the manual thickness control cranks, for example; see Section 15), as well as incorrectly mounted automatic grade controls (see Section 16), can cause a long-wave problem. If a stringline is being used as a grade reference, a sag in that line between support posts can also be a cause of long waves (see Section 16). Another factor contributing to long-wave roughness is improper delivery of the mix to the paver, particularly if the haul truck bumps into the paver or if the truck driver holds the brakes while the truck is being pushed by the paver (see Section 13). One additional factor can be the condition of the underlying surface: the long waves may be a reflection of the waves in the base material.

Long waves may also be found at those points where the compaction equipment reverses direction. This problem is most prevalent when the asphalt layer being placed is more than about 100 mm (4 in.) thick. The problem may be exacerbated when the maximum-size aggregate used in the mix is relatively small compared with the lift thickness. The waves are caused by a bow wave that forms in front of the roller when the mix is tender.

In terms of mix design, long waves can be caused by truckload-to-truckload segregation of the mix and by changes in mix temperature (see Section 3). Both of these deficiencies cause the forces on the screed to vary, resulting in a wavy surface. The compaction equipment can also create a wavy mat if the roller operator turns or reverses the machine too abruptly.

Roughness or washboarding is normally caused by improper operation of a vibratory roller (see Section 18). This type of equipment should be operated at as high a frequency as possible and at an amplitude setting related to the thickness of the layer being compacted—usually a higher amplitude setting for a thicker layer of mix and a lower amplitude setting for a thinner lift. Further, the washboard effect can be worse if the roller is operated at a high speed, particularly if the frequency setting is less than 2,400 vibrations per minute.

Solutions

Short waves (ripples) can be eliminated only by preventing their formation. The most important factor in preventing short waves is to keep the amount of mix (head of material) in front of the screed as consistent as possible. In addition, the stiffness of the mix, which is related to both its temperature and its composition, should be maintained as constant as possible. The amount of mix is controlled by properly setting the hopper flow gates and by keeping the slat conveyors and augers operating as much of the time as possible (close to 100 percent) while the machine is moving forward. Mix stiffness is controlled at the asphalt plant by keeping the mix temperature, aggregate gradation, and fluids content (asphalt content plus moisture content) as constant as possible. Any factors that cause either the volume or stiffness of the mix at the screed to change can cause short waves or ripples in the HMA mat.

Surface waves caused by problems with automatic grade controls can be detected by shutting off the grade controls and determining whether the waves continue to form. If the grade controls are at fault, the operation and maintenance manual supplied with those controls should be consulted to determine the proper corrective action. Sags in a stringline reference can be found by sighting down the line as the grade sensor wand passes along the string. Short or long waves caused by the mechanical condition or operation of the paver screed can usually be detected by careful observation of the paver during mix laydown. The long waves formed by incorrect operation of the haul truck or compaction equipment can also be detected easily by observing those operations.

If washboarding is caused by incorrect operation of a vibratory roller, a change should be made in one or more of the following: the vibratory amplitude setting, the vibratory frequency, and the speed of the roller.

Effects on Performance

Long-term pavement performance is affected by surface waves, both short and long, in two ways. First, the waves reduce the smoothness of the pavement, which lowers the pavement condition rating or the present serviceability index of the roadway. The structural performance of the pavement will be changed, however, only if the waves are severe enough to increase the dynamic or impact loading of the pavement under heavy truck traffic. Second, short waves and the factors that cause them can affect pavement density levels. A tender mix is generally more difficult to compact properly than is a stable mix; the result may be a decrease in density and a corresponding increase in air void content.

Washboarding is basically roughness built into the pavement surface during the compaction operation. Because it affects the degree of density obtained during the compaction process, this type of defect can significantly reduce the long-term durability of the pavement layer. In addition, washboarding contributes to a rough ride for the vehicles using the pavement.

TEARING (STREAKS)

Description

There are three general types of mat tearing, or pulling of the asphalt mix under the screed of the paver. The three types are defined by the location of the tear marks in the mat: (*a*) in the center of the lane, (*b*) on the outside edges, and (*c*) across the full lane width.

Causes

A gearbox streak can sometimes be seen in the surface of the mat directly behind the center of the main screed. This streak is typically 150 to 200 mm (6 to 8 in.) wide and is normally caused by a lack of asphalt mix being pushed under the auger gearbox located in front of the center of the screed. This lack of mix may be the result of improper flow gate settings—not enough mix being fed back to the screed. It is more likely to be caused, however, by missing, worn, or improperly set reverse augers or paddles on the augers (located adjacent to the gearbox) that are used to force mix underneath the gearbox. (See Section 15.)

A gearbox streak is often thought to be a type of segregation. It is not. The rough surface texture is the result of a lack of mix at that point in the pavement width—less mix passes under the screed at the auger gearbox than passes under the screed on either side of the gearbox. The rougher texture, or tearing, makes the surface appear more open or segregated. Gearbox streaks are more prevalent with harsher mixes—those containing larger-size aggregate, more crushed aggregate, or lesser amounts of asphalt.

A centerline streak can also be caused by improper setting of the crown on the main paver screed. The appearance of streaks behind the screed is caused primarily by an improper relationship between the crowns at the leading (front) and trailing (back) edges of the screed. A tearing or open texture about a meter (several feet) wide in the center of the mat may be caused by a lack of lead crown in the screed. Conversely, a tearing or open texture along both outside edges of the asphalt mixture is normally caused by an excess of lead crown in the screed. For most mixes, the lead crown of the screed should be set slightly higher [approximately 3 mm (⅛ in.)] than the tail crown. A proper relationship between lead and tail crowns will result in a uniform texture of the mat across its full width. Edge streaks can be caused by improper flow gate settings or incorrect installation of the screed extensions. Partial-width tearing can also result from a cold screed plate if the screed has not been uniformly preheated before paving begins. (See Section 15.)

Full-width tearing of the mat can be attributed to a number of factors. One such factor is warped or worn screed plates. Another is the forward speed of the paver being too high for a particular mix. The use of a mixture with aggregate that is large compared with the mat thickness being laid can also be responsible for full-width tearing of the mat. A good rule of thumb for the relationship between the maximum aggregate size in the mix and the minimum compacted course thickness is that the depth of the compacted layer should be at least twice the largest coarse aggregate particle size or three times the nominal maximum aggregate size. Thus a mix containing a maximum aggregate size of 19.0 mm (¾ in.) [nominal maximum aggregate size of 12.5 mm (½ in.)] should be placed at least 38 mm (1½ in.) thick. Lastly, cold mix temperatures, particularly when combined with a cold paver screed, can significantly affect the amount of tearing that occurs. (See Section 15.)

Solutions

A gearbox streak can usually be eliminated only by changing the amount of mix being forced under the screed at the auger gearbox. This change is made by installing reverse paddles or reverse augers on each side of the gearbox in order to push more mix under the gearbox. If the paver is already equipped with such devices, they should be checked to see whether they are worn and need to be replaced.

Constant center or outside edge mat tearing can usually be eliminated by adjusting the relationship between the lead and tail crowns on the paver screed. If this change does not solve the problem, the setting of the paver flow gates should be modified. Full-width tearing can be eliminated by increasing the mix temperature, preheating the screed properly before paving starts, replacing warped or worn screed plates, or increasing the lift thickness.

Effects on Performance

Tearing of the mat affects long-term pavement performance by causing changes in density in those areas where the tearing has occurred. Torn areas may appear segregated and are usually deficient in mix quantity. Pavement performance will be reduced in relation to the degree to which the tearing reduces the density and increases the air void content of the mat. In addition, the torn areas will be more susceptible to raveling and to the effects of moisture (stripping).

NONUNIFORM TEXTURE

Description

Nonuniform mat texture (see Figure 19-1) can be described as differences in the appearance of the mix, both transversely and longitudinally, as it is placed and compacted. Normally, minor differences in surface texture will be apparent because of differences in the alignment of the larger coarse aggregate particles as the mix passes out from beneath the paver screed. In addition, a mix with a higher fine aggregate (sand) content will have a more uniform surface texture than a mix containing a larger percentage of coarse aggregate.

Causes

Many factors related to the operation of the asphalt paver affect the uniformity of the surface texture of the mix. (See Section 15.) A variable amount of mix against the screed, caused by overloading the augers or running the hopper empty between truckloads, can cause variations in the amount of mix tucked under the screed and thus produce a nonuniform texture. Improper screed maintenance,

FIGURE 19-1 Nonuniform mat texture after compaction.

including worn or loose screed plates or screed extensions incorrectly installed, as well as low screed vibratory frequency, may alter the mat texture and cause nonuniformity. In addition, a low mix temperature, caused either by plant problems or by the paver sitting too long between truckloads of mix, can be a factor in uneven mat texture, especially if the paver screed is also cold. The tearing that results when the compacted layer thickness is less than twice the dimension of the largest aggregate particles (as discussed above) is still another contributing factor.

A soft or yielding base under the course being constructed may cause the new layer to have a variable surface texture (see Section 14). Moreover, segregation of the mix caused by poor mix design (Section 3) or improper handling of the mix during mixing (Section 3), loading (Section 11), hauling (Section 11), unloading (Section 13), or placing (Section 15) operations can contribute to a nonuniform surface texture. The variability of the texture will be affected as well by any factors that cause nonuniformity in the mix, such as deviations in aggregate gradation, asphalt content, or mix temperature (see Section 3).

Solutions

The solutions for nonuniform surface texture are as varied as the causes. Paver operation, particularly with regard to the need for a constant head of material in front of the screed, should be monitored closely. The paver and screed should both be well maintained and in good operating condition. The compacted thickness of the mat being placed should be designed so that it is at least twice the size of the largest coarse aggregate particles incorporated into the mix. Finally, a mix that is tender, variable in aggregate gradation or asphalt content, or easily segregated should be modified to increase its stiffness and improve its properties before it is produced at the plant and delivered to the paver for laydown.

Effects on Performance

Nonuniform surface texture is usually associated with nonuniform density. The same compactive effort will generally achieve lower density in areas in which the coarse aggregate has been dragged by the paver screed or segregation of the mix has occurred, as compared with areas having uniform surface texture. As density decreases and air void content increases, the durability and serviceability of the asphalt mat decrease markedly.

SCREED MARKS

Description

Screed marks are transverse indentations in the surface of the asphalt mat. They occur when the paver stops between truckloads of mix. Depending on the mixture being placed, some screed marks are barely noticeable, whereas others are very distinct and deep. Screed marks can also occur in the longitudinal direction when rigid or hydraulic extensions are used and the elevation of the extension is not the same as that of the main screed.

Causes

There are several causes of transverse screed marks. (See Section 15 for a discussion of screed operations.) One is excessive play in the mechanical connections on the screed. Such marks also result when the screed is set up incorrectly and rides heavily on its rear end. If the asphalt mix is tender and if the paver is equipped with a very heavy screed, such as hydraulic extensions with additional rigid extensions attached, the screed will tend to settle into the mix and leave marks. If any of these causes are involved, the screed marks will be visible each time the paver stops.

Another cause is the haul truck bumping into the paver when preparing to discharge the mix or the truck driver holding the brakes on the truck when the paver starts to push the truck. In these cases, the screed marks will appear only when the truck–paver interchange is improper.

Longitudinal screed marks are caused by improper setting of the screed extensions relative to the main screed. When extensions are used, their vertical position and angle of attack must be the same as those of the main screed. If rigid extensions are set at the wrong elevation, a longitudinal mark will occur at the point where the different screed sections are joined. If hydraulic extensions are used, two longitudinal marks may occur—one at the end of the main screed and one at the inside edge of the extension on each side of the machine.

Solutions

If the transverse screed marks are a result of the mechanical condition or improper setup of the paver screed, the screed should be repaired. If the marks are caused by the truck bumping into the paver, the laydown operation should be altered so that the paver picks up the haul truck instead of the truck backing into the paver. In addition, once the paver has established contact with the truck, the truck driver should apply only enough pressure to the brakes to keep the truck in contact with the paver.

In some cases, particularly if the mix is very tender, screed marks can be eliminated by not stopping the paver between truckloads of mix. This can be accomplished by using a windrow elevator or material transfer vehicle to deliver mix to the paver hopper. If dump trucks are used to haul the mix, however, it is generally better to stop the paver between truckloads of material (stopping and restarting the paver as quickly as practical) instead of allowing the paver operator to run the paver hopper dry, reduce the head of mix in front of the paver screed, and increase the opportunity for truckload-to-truckload segregation.

To achieve uniform surface texture, the elevation and angle of attack of the screed extensions must be matched to those of the main screed. Longitudinal screed marks caused by improperly setting the elevation of the extensions can be eliminated by correcting the position of each extension relative to that of the main screed. Adjustments to both the vertical position and the angle of attack of the extensions may be needed. These adjustments should be made whenever hydraulic or rigid extensions are used.

Effects on Performance

Transverse screed marks generally are not detrimental to the durability of the mat. They may, however, affect the ride by creating a bump whenever the marks cannot be completely rolled out by the compaction equipment. In many cases, the screed marks have less of an effect on the performance of the mix than does the slowdown and startup of the paver when the operator attempts to keep it moving as the empty truck pulls away and the loaded truck backs into the hopper.

Longitudinal screed marks indicate that the level of the mix under the screed extensions is different from that under the main screed. If the screed marks are severe, differential compaction may occur across the mark or "joint," with the compaction equipment initially riding on the higher mat. The marks can leave a ridge in the mix if they cannot be completely rolled out.

SCREED RESPONSIVENESS

Description

As the thickness control cranks on the screed are changed, the screed's angle of attack increases or decreases. As the paver moves forward to place the mix, the screed moves up or down to the new equilibrium point for the newly set mat thickness. When the screed fails to respond to changes in the setting of the thickness control cranks, the operator is unable to alter the depth of the layer being placed. The paver also loses its inherent ability, through the principle of the floating screed, to provide the self-leveling action needed to place a smooth asphalt mat.

Causes

An extremely high paver speed [more than 25 m (83 ft) per minute for thin lifts or more than 15 m (50 ft) per minute for layers more than 63 mm (2½ in.) thick] may cause a lack of responsiveness of the screed (see Section 15). The mechanical condition of the screed affects its ability to react. The screed riding on its lift cylinders or loose connections on the thickness control cranks will cause the screed to be unresponsive. If automatic grade controls are used (see Section 16), an incorrect sensor location will render the screed unable to react to input signals from the grade sensors.

If the maximum aggregate size used in the mix is too great compared with the depth of mix being placed, the screed will ride on or drag the largest aggregate pieces. As a result, the screed will be unable to change its angle and will thus be unresponsive to changes in the thickness control settings. Variations in mix temperature will also cause the screed to be unresponsive to changes in the angle of attack because the mix stiffness variations themselves will cause the screed to continually seek new equilibrium levels for the forces acting on it.

Solutions

The paver and screed must be in good operating condition. The sensor for automatic grade controls must not be located either at the tow points or behind the pivot points of the screed; rather, it should be located in the area between one-third and two-thirds of the length of the leveling arms. If the mix texture is uniform (indicating a proper relationship between course thickness and maximum aggregate size), the screed will be able to respond to changes in the thickness control settings.

Effects on Performance

An unresponsive screed causes a rough asphalt mat. The screed is unable to react to manual changes in the thickness settings. It also loses its ability to self-level on an existing pavement surface because it cannot reduce the thickness of mix placed over the high points in that surface and increase the thickness placed in the low areas.

Thus the ridability of the course being placed can be affected significantly if the paver screed is unresponsive.

SURFACE (AUGER) SHADOWS

Description

Surface (auger) shadows are dark areas that appear in the surface of an HMA mix. In most cases, the shadows cannot be seen until some time after the pavement has been used by traffic and some of the asphalt cement film has been worn off the exposed aggregate particles by the vehicle tires. Surface shadows are seen most easily when the sun is low on the horizon and the pavement is viewed when looking toward the sun. The shadows are also visible when the pavement surface is damp or when the surface is viewed from the shoulder of the roadway at night and vehicle headlights are shining on the surface.

In severe cases, surface shadows may be visible immediately behind the screed during the laydown operation. Even in this latter case, the shadows will disappear when the mix is being compacted by the rollers, only to be visible again later under the conditions described above. The shadows may be completely across the lane width being placed, or they may be only partially across the width. The extent of the shadows depends on how the paver is operated, particularly the portion of on to off time of the augers on each side of the machine.

Causes

Surface shadows are caused primarily by overloading of the augers on the paver (see Section 15). If the head of material in the auger chamber is large enough to "bury" the augers, the screed will react to the variable forces acting on it. The spacing between the shadows will normally correspond to the starting of the augers when operated in a stop–start manner. Whenever the amount of mix in front of the screed is at or above the top of the augers, the shadows will be formed and seen later in the pavement.

On most pavers it is possible to adjust the distance between the screed and the tractor unit. This is accomplished by unbolting connections on the leveling or tow arms of the paver and moving the tractor forward (or backward) while the screed remains stationary on the pavement surface. Depending on the make and model of the paver, there is typically a 100-mm (4-in.) length of slide for the screed connection. The severity of surface shadows may increase with the screed in the back position—when more mix is being carried in the auger chamber and the augers are being overloaded.

The shadows are thought to be the result of a slight increase in mix density caused by the restarting of the augers and the subsequent forcing of additional mix under the screed. There is no difference in surface texture associated with the location of the surface shadows; they can be seen only from an angle. Their intensity often increases when a tender mix is being laid.

Solutions

The HMA mixture carried in the auger chamber should be maintained at a level near the center of the auger shaft. This means the flow gates should be set so that the augers operate as close to 100 percent of the time as possible and stopping and starting of the augers is minimized. In no case should the top of the augers be completely covered with mix. Further, the location of the screed should be set as far forward as possible so that the amount of material in the auger chamber is reduced and the head of material in front of the screed is kept to a minimum. The screed should not be set in the back position unless a large-stone mix [one in which the maximum size of the aggregate is more than 37.5 mm (1½ in.)] is being placed.

Effect on Performance

Surface shadows are not necessarily detrimental to the performance of the mix, except for a minor effect on ridability. The difference in the density of the mix in areas with and between shadows is generally not great enough to be determined accurately. The main concern with surface shadows is the visual appearance of the mix to vehicle drivers.

POOR PRECOMPACTION

Description

A modern asphalt paver is normally equipped with a vibratory screed. This type of screed allows the mix to be partially compacted as it passes beneath the screed. Depending on such variables as forward paver speed, layer thickness, mix temperature, and ambient environmental conditions, the density of the asphalt mixture measured behind the screed before compaction is usually in the range of 70 to 80 percent of the theoretical maximum density (a voidless mix).

A few pavers are equipped with combination screeds, which have both tamper bars and vibrators. At slow paver speeds, the combination screed typically achieves greater compaction of the mix than is obtained with the vibratory screed alone. At paver speeds greater than 7.5 m (25 ft) per minute, however, the increased compactive effort achieved with the tamper bar is typically lost, and the degree of compaction obtained is similar to that achieved with a simple vibratory screed.

Causes

The amount of precompaction achieved with the screed decreases as the paver speed increases (see Section 15). Precompaction generally increases slightly as the frequency of the screed vibration increases. Precompaction decreases significantly, however, if the screed is riding on the screed lift cylinders, thereby limiting the available compactive effort. The level of precompaction obtained is also limited if the mat is too thin for the maximum aggregate size used in the mix (less than twice the largest-size aggregate; see the earlier discussion of nonuniform texture), if the mix being placed is too cold, or if the base on which the new layer is being laid is soft and yielding.

Solutions

Decreasing the paver speed and increasing the frequency of vibration of the screed should, within limits, increase the level of precompaction achieved during the laydown operation. It is also possible on some pavers to increase the amplitude of the vibration in order to increase the impact force of the screed on the mix. Proper maintenance of the screed helps as well in obtaining a uniform compactive effort from the screed.

Effects on Performance

As long as the required density level is obtained using conventional rollers behind the paver, the level of precompaction accomplished by the screed will not affect the long-term performance of the HMA layer. It may be possible, however, to reduce the number of roller passes needed to meet the density and air void content criteria if the amount of precompaction obtained by the screed is higher. In addition, increased precompaction density can reduce the amount of differential compaction that occurs in low spots and rutted areas.

JOINT PROBLEMS

Description

Poor transverse joints are associated either with a bump at the joint, a dip in the pavement surface several meters (feet) beyond the joint, or both. Poor longitudinal joints (Figure 19-2) between passes of the paver are

FIGURE 19-2 Poor longitudinal joint due to unsatisfactory workmanship.

usually characterized by a difference in elevation between the two lanes, by a raveling of the asphalt mix at the joint, or both. The area adjacent to the longitudinal joint is usually depressed below the level of the surrounding pavement surface.

Causes

Joint problems are caused by poor construction of the joint, inadequate compaction of mix placed along the joint, improper start-up procedures when paving resumes after a stoppage, or improper construction and removal of tapers.

Solutions

One key to a good transverse joint is to construct the joint at the end of the paving day at a location in the mat where the layer thickness is constant. (See Section 17 for a discussion of joint construction.) This means the compacted thickness of the mat at the end of the paver run is the same as that of the previously placed mat.

At the start of paving the following day, the paver screed should be placed on blocks on the cold side of the transverse joint. The thickness of the blocks should be related to the depth of the course being laid—approximately 5 mm (¼ in.) thick for each 25 mm (1 in.) of compacted layer thickness. The front edge of the paver screed should then be placed directly over the vertical face of the joint. Once the paver pulls away from the joint, the right amount of mix should be in the right place, and only minimal raking, if any, normally needs to be done. The mix at the joint should then be compacted as quickly as possible.

For longitudinal joint construction, it is extremely important to compact the edge of the first lane properly. Doing so requires that the vibratory or static steel wheel roller hang out over the unsupported edge of the mat by about 150 mm (6 in.). This practice provides the most compactive effort along the unconfined edge without causing undue lateral displacement of the mix along the edge of the pavement.

When placing the second (adjacent) pavement lane, the end plate on the paver screed should overlap the first lane by 25 to 40 mm (1 to 1½ in.). Minimal raking, if any, should be done on the mix placed over the first lane. The rollers—vibratory, pneumatic tire, and static steel wheel—should operate on the hot side of the joint and extend over the joint on the cold side by approximately 150 mm (6 in.). The same number of roller passes should be made over the longitudinal joint as over each point in the interior of the HMA mat.

Effects on Performance

A poor transverse joint will not affect pavement performance to any significant degree if proper density levels are obtained by the compaction equipment. A poor ride will usually be the only negative result. An improperly constructed longitudinal joint, however, can seriously decrease the serviceability of the pavement structure. A poorly placed and compacted joint will ravel and cause one side of the joint to be lower than the other. If the density level is too low, the whole pavement layer thickness at the longitudinal joint may wear away under the action of traffic. A poor joint will also be porous, allowing water to enter the underlying pavement courses.

CHECKING

Description

Checking can be defined as short transverse cracks, usually 25 to 75 mm (1 to 3 in.) in length and 25 to 75 mm (1 to 3 in.) apart, that occur in the surface of the HMA mat at some time during the compaction process (see Figures 19-3 and 19-4). The checks are not visible immediately behind the paver screed. Rarely does checking occur during the first or second pass of the compaction equipment over the mat. If checking is going to occur, it will normally take place after the mix has cooled to a temperature of less than 115°C (240°F) and additional passes of vibratory or static steel wheel rollers (or both) are made over the mat. Checking does not usually occur when the mix is compacted with a pneumatic tire roller.

Most HMA mixtures do not check at all during compaction, whereas others exhibit tender characteristics and check readily. As checking becomes severe, the cracks become longer and are spaced closer together. The cracks do not extend completely through the depth of the course, but are only 10 to 13 mm (⅜ to ½ in.) deep.

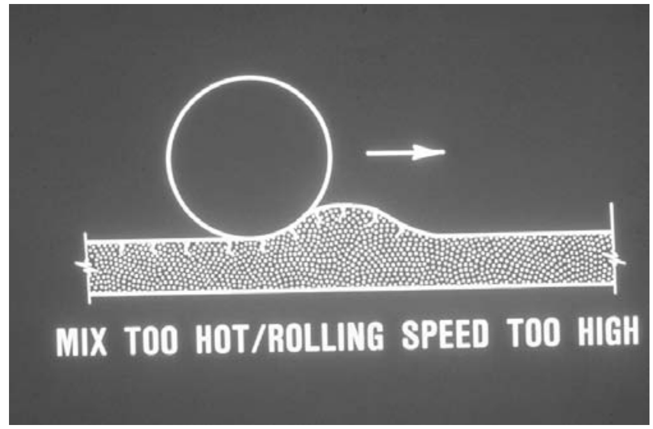

FIGURE 19-3 Roller checking during compaction.

Causes

A mix that checks during compaction is a tender mix. The mix shoves or moves in front of the drums on either vibratory or static steel wheel rollers. Checks or cracks are formed when a bow wave occurs in front of the roller drums as the mix moves longitudinally before the roller reaches that location.

Checking may be caused by two primary factors: (*a*) excessive deflection of the pavement structure under the compaction equipment (see Section 14) and (*b*) one or more deficiencies in the asphalt mix design (see Section 3). A mix that checks is not internally stable enough—does not have enough internal strength at elevated temperatures—to support the weight of the compaction equipment during the rolling process.

FIGURE 19-4 Hairline cracks caused by roller checking.

When a yielding foundation is the cause of the checking problem, the underlying pavement on which the new HMA layer is being placed is weak and yields under the movement of the compaction equipment (see Section 14). The weight of the rollers causes the layers in the pavement structure to move, shove, and bend excessively, placing the new mix in tension at its surface. The check marks are then formed when the surface of the new HMA is pulled apart as the pavement structure deflects during the rolling operation. The checks should appear in the new mix surface only at locations where there is movement of the pavement structure under the compaction equipment. If the paver passes over a soft spot in the underlying structure, for example, the checking should occur only where the soft spot exists.

A more common cause of checking is one or more deficiencies in the HMA mixture: (*a*) an excess of fluids in the mix—too much asphalt cement or too much moisture in the mix, or both; (*b*) a hump in the sand gradation curve—too much midsize sand material [1.18-mm and 0.600-mm (No. 16 and No. 30) sieve size] and too little fine sand material [0.300-mm and 0.150-mm (No. 50 and No. 100) sieve size]; and (*c*) a lack of room in the aggregate gradation for the asphalt cement (low VMA).

An excess of fluids in the HMA mix makes the mix tender and allows it to be displaced easily under the applied compactive effort of the rollers. The mix will be tender if the binder content is too high for the gradation and characteristics of the aggregate used, particularly if the mix has a low VMA content. If the mix contains too much moisture because the aggregate was not completely dried when passing through the batch plant drier or drum mixer (parallel flow or counter flow), the excess moisture will act as asphalt cement at elevated temperatures and overlubricate the mix. The moisture remaining in the aggregate pores will prevent the binder material from entering those pores in the aggregate, in effect leaving more binder material between the aggregate particles instead of partly inside the aggregate.

If tenderness is due to an excess of asphalt cement in the mix, checking should occur in the mix on a regular, daily basis. If tenderness is due to an excess of moisture in the mix, checking should occur whenever the plant is not being operated properly. For example, checking may occur in the mat the day after a rain, but not the day before. If operations at the asphalt plant do not include removing the extra moisture in the aggregate resulting from the rainfall on the stockpiles, that moisture will add to the asphalt binder fluids and cause the mix to be tender.

A hump in the fine aggregate gradation curve—an excess of midsize sand in the mix—can also cause the mix to be tender. In addition, mixes low in VMA content will generally be tender and move easily under the force of a vibratory or static steel wheel roller. Further, the various characteristics of the aggregate particles, such as surface texture, angularity, crushed faces, and amount of dust coating, can play a major role in the amount of checking that occurs during compaction. Mixes that are deficient in fine aggregate gradation or lack adequate VMA content will normally check continuously, not periodically. If the sand gradation is variable, however, checking may occur only when the sand gradation is improper.

The above mix deficiencies are compounded, and the amount of checking that occurs may be increased, when the mix temperature is too high for the particular asphalt cement grade being used in the mix. As the mix temperature increases, the viscosity of the asphalt cement decreases, causing the mixture to be more tender. An additional factor that can affect the amount of checking is the temperature susceptibility of the asphalt cement itself: the greater the degree of temperature susceptibility of the binder material, the more checking may occur in the HMA mix.

Occasionally, checking can be caused by temperature differentials within a layer of HMA mix (heat checking). On a cool day and under windy conditions, the temperature of the mix that is in contact with the existing pavement surface may decrease quickly. The top surface of the mix will also cool quickly. The temperature of the mix in the middle of the layer, however, will remain high. This temperature differential can cause the mix to check under the compactive effort of the rollers.

There are also a number of secondary causes of checking. One is a mix whose temperature is too high: the mix was overheated in the plant. In addition, improper rolling techniques can cause checking—rolling too fast, stopping too quickly, making sharp turns on the hot mat, or making an excessive number of passes with the finish roller or finish rolling when the mat is still at too high a temperature (see Section 18). Finally, checking may be increased by a poor bond between the new mat and the underlying surface because of a dirty surface or the lack of a tack coat.

Solutions

If checking is caused by the presence of a yielding foundation underneath the new HMA layer, the solution is to repair and properly prepare the existing pavement structure before the new HMA layer is placed. Soft spots should be removed and replaced. All areas of excessive deflection should be removed and replaced or stabilized. Uniform support is needed in the underlying pavement structure if the new pavement layers are to perform adequately.

If checking is caused by a deficiency in the mix design—an excess of fluids in the mix or a problem with the gradation of the fine aggregate or the VMA content of the mix—the long-term solution is to change the mix properties. Those changes must be made at the asphalt plant and cannot be made at the paving site. If the mix contains an excess of fluids—either asphalt cement or moisture—the binder content should be reduced or the aggregate properly dried to remove all of the moisture. In some cases, the production rate of the plant will have to be reduced for the moisture to be completely removed from the aggregate. In other cases, plant operating conditions may need to be changed (e.g., flights, drum angle).

If checking is caused by the gradation of the fine aggregate incorporated into the mix, the gradation should be changed. It may be necessary to increase or decrease the amount of fine aggregate used, add a small amount of fine aggregate with a different gradation, increase the angularity of the fine aggregate, or use a completely different material from a different source. If checking is caused by a lack of VMA in the HMA mix, changes need to be made to increase the VMA.

Checking is often thought to result from the mix being too hot. This is only partially correct; the mix is too hot at some temperatures to support the weight of the compaction equipment because the mix lacks internal strength and stability. If the mix were properly designed, it would not be too hot to be compacted at any temperature below about 150°C (300°F). Most checking occurs when the mix temperature is decreasing from about 115°C (240°F) down to about 90°C (190°F); rarely does checking occur when the mix temperature is above approximately 115°C (240°F) or below approximately 90°C (190°F).

In the short term, changes in both the rolling zone and the type of rollers used to densify the mix can be made to reduce the amount of checking that occurs. If the mix is tender because of excess fluids, a problem with the fine aggregate gradation, or lack of VMA, it may be possible to densify the mix properly at an elevated temperature without causing the checking.

A mix that checks is tender, but this mix can usually be compacted satisfactorily at high temperatures—above 120°C (250°F). The required level of density can generally be obtained if enough roller passes can be applied to the mix before it cools to the point at which the checking begins. This can be done by using two breakdown rollers instead of one—using two rollers operating in echelon (side by side) instead of using a breakdown roller followed by an intermediate roller. The two breakdown rollers each apply their compactive effort to one side of the newly placed lane. Many passes are made over each point in the pavement surface before the mix begins to check. Once checking starts, the rolling process is temporarily suspended.

If compaction operations are attempted when the mix is moving, shoving, and checking under the action of vibratory or static steel wheel rollers, the mix will decompact rather than compact. Rolling should not be carried out with steel wheel rollers when the mix is tender and checking. Most tender mixes will remain tender until the surface of the mix cools to a temperature of approximately 90°C (190°F). At this temperature, the mix has cooled sufficiently so that the viscosity of the asphalt binder has increased to the point where the mix can again support the weight of the compaction equipment. Static steel wheel rollers can then be used to achieve the final density in the mix and remove any roller marks in the pavement surface.

When a tender mix is in the middle temperature range, between about 115°C (240°F) and 90°C (190°F), rolling should not be attempted, as discussed above, with either vibratory or static steel wheel rollers. A pneumatic tire roller, however, can be used in this temperature zone since the rubber tires on this roller will typically not shove the mix and a bow wave will not form in front of the tires. The tender mix will densify, instead of check, under the compactive effort of the pneumatic tire roller. Finish rolling using a static steel wheel roller can be completed once the mix has cooled to a temperature below about 90°C (190°F).

In most cases when checking occurs in the mix, the roller operators tend to back off the mix and allow it to cool. This is the wrong approach to the problem. Delaying the compaction permits the mix to cool and stiffen but most often does not then allow enough time for the mix to achieve the required level of density. With a tender mix, it may not be possible to accomplish both objectives (no checking and adequate density) at the same time if the mix is allowed to cool before rolling operations are started. It is much better to compact the mix as much as possible before checking starts, stay off the mix in the middle temperature zone when checking is most likely to occur, and then finish roll the mix once it has cooled enough to support the weight of the final roller.

If the mix delivered to the paver is too hot—above 165°C (325°F)—it should be allowed to cool after laydown before the compaction process is started. Improper rolling techniques should be corrected. The surface of the underlying pavement should be clean and properly tack coated before placement of the new mix begins.

None of the solutions to the checking problem will work in all cases. Each mix will have its own compaction characteristics. For some extremely tender mixes, checking may occur at a wider range of temperatures, from as high as 130°C (270°F) down to as low as 75°C (170°F). As noted, mixes that lack internal stability will generally check under steel wheel rollers (operated in either the vibratory or static mode), and thus these mixes should be redesigned.

Effects on Performance

Although checks extend only a short distance down from the surface, they are highly detrimental to long-term performance because the tender mix characteristics affect the level of density obtained. If the rollers are kept back from the paver in an attempt to decrease the amount of checking that occurs, the level of density obtained by the compaction equipment will normally be reduced significantly. Thus the air void content of the HMA mat will increase. A mix that contains checks will therefore lack density and have a greatly reduced pavement life under traffic.

SHOVING AND RUTTING

Description

Shoving of an HMA layer is displacement of the mixture in a longitudinal direction. Such displacement may take place during the compaction operation or later under traffic. In most cases, shoving during construction is accompanied by a large bow wave in front of the breakdown roller, particularly if that roller is a vibratory or static steel wheel machine. Shoving may also occur in conjunction with mix checking if the mix is tender enough as a result of faulty aggregate gradation or excess fluids (asphalt binder or moisture) content. Finally, mat or mix shoving can occur at the reversal point of the rollers, especially at the location closest to the paver. A pavement layer that has shoved under the action of traffic is shown in Figure 19-5.

Rutting, illustrated in Figure 19-6, shows displacement of the mixture in both vertical and transverse directions. Rutting occurs when heavy traffic passes over an unstable mix. In a few cases, the rutting is purely vertical (consolidation rutting). In this situation, the mix was not adequately compacted at the time of construction, and the traffic loads are essentially finishing the compaction process. The most common form of rutting is transverse distortion—the mix distorts or shoves transversely as a result of lateral flow of the mix under applied traffic loads.

FIGURE 19-5 Shoving due to unsatisfactory mix.

Causes

Shoving and rutting are due primarily to an unstable HMA mixture (see Section 3). This instability can be caused by the same variables that are responsible for checking—an excess of fluids (asphalt binder or moisture) in the mix, a hump in the fine aggregate grading curve, or the properties of the aggregate and the asphalt cement. A mix that has a high Marshall or Hveem stability may still distort longitudinally under the compaction equipment and later both longitudinally and transversely under traffic. Shoving and rutting can be highly prevalent when a sand mix is placed in a thick layer [more than 40 mm (1½ in.)] at a high temperature [more than 140°C (280°F)]. Further, thicker lifts in pro-

FIGURE 19-6 Rutting of unstable asphalt mixture.

portion to the maximum-size aggregate used in the mix will tend to shove more than thinner lifts with the same aggregate size and grading.

Improper roller operation, particularly sudden reversal of the roller, can also contribute to the shoving of the mix during construction (see Section 18). If a vibratory roller is run at too great a speed and the impact spacing is too far apart, the mat may develop a washboard effect, where the peak-to-peak distance is equivalent to the impact spacing. Washboarding or shoving is more likely to occur at normal frequencies but at high speeds where the impact force is greater. If a pneumatic tire roller with high tire pressure is used for breakdown compaction, a tender mix may shove laterally under the tires. Shoving can occur under any roller that is operated improperly.

Another possible cause of shoving is an excess of tack coat material that may be pulled into the mix. In a similar manner, excess asphalt from a bleeding underlying surface or from joint filler material can be pulled into the mix and increase its fluidity and tenderness. Shoving may occur as well when the underlying surface is dusty or dirty—a slippage failure. (See Section 14.)

Solutions

The solution to a mix that shoves under the compaction equipment is to increase its internal stability. This can be accomplished by reducing the fluids content (asphalt or moisture, or both) of the mix, but only after determining the effect of a change in asphalt binder content on the mechanical properties of the mix. The internal friction can be increased by lowering the mix temperature. Alternatively, the internal friction among the aggregate particles can be increased by changing the aggregate gradation or increasing the amount of angular (crushed) particles in the mix.

The compaction process for a tender mix should be changed, as discussed above under checking, to obtain sufficient density at the time of construction. An increase in the density achieved during the construction process will generally reduce the amount of shoving and rutting that may occur later under applied traffic. Sand mixes, because of their inherent tender nature, should be placed in several thin layers instead of one thick layer when used as base or binder courses.

The compaction equipment should be operated properly so as to reduce the opportunity to displace the mix during the rolling operation. Further, if the underlying pavement surface is dirty, it should be cleaned and a proper tack coat applied.

Effects on Performance

Mats that tend to shove under the compaction equipment are basically unstable. These mixtures will usually continue to distort under traffic, both longitudinally and laterally. Shoving of the HMA mixture during construction is a strong indication that the pavement will rut later and not perform properly under traffic.

BLEEDING AND FAT SPOTS

Description

Bleeding of an asphalt mixture (see Figure 19-7) occurs when the asphalt cement flows to the top of the mix surface under the action of traffic loading. Bleeding is often seen as two flushed longitudinal streaks in the wheelpaths of the roadway. Fat spots in an asphalt mixture (Figure 19-8) are isolated areas where asphalt cement has come to the surface of the mix during the laydown and compaction operation or later under traffic. These spots can occur erratically and irregularly, or they may be numerous and in a fairly regular pattern.

Causes

Fat spots are caused primarily by excessive moisture in the mix (see Section 3). The problem is more common with mixtures that contain a high percentage of fine aggregate (oversanded mixes) and those that contain aggregates with a high porosity. If all the moisture in the coarse and fine aggregate is not removed during the drying and mixing operation at the asphalt plant, the moisture vapor will force asphalt cement to the surface of the mix behind the paver as the moisture escapes from the mix and evaporates. Fat spots occur more frequently when aggregate stockpiles are wet or when the moisture

FIGURE 19-7 Asphalt bleeding in travel lane.

FIGURE 19-8 Fat spot caused by localized excess asphalt.

content varies in different portions of the stockpiles. Fat spots sometimes occur in areas where petroleum products, such as oil and diesel fuel, were spilled onto the pavement surface prior to overlay (see Figure 19-9; see also Section 14) or have contaminated the mix. In addition, fat spots can be associated with segregated areas in the mix. If the mix deposited on the roadway by the paver is segregated, areas in which excess asphalt cement is present in the mix can result in free binder material on the top of the layer being placed.

The causes of bleeding normally fall into two categories. The first is an excess of fluids in the asphalt mixture—either asphalt cement or moisture or both. Under traffic, the extra moisture and asphalt cement will be pulled to the surface by the passage of vehicle tires. This bleeding phenomenon usually occurs on new mix and during hot weather when the viscosity of the asphalt cement is at its lowest level. Typically the bleeding occurs shortly after traffic is allowed to travel over the fresh mix—while there is still some moisture in the mix and while the viscosity of the asphalt cement binder is still relatively low.

FIGURE 19-9 Fat spot caused by fuel oil spill prior to overlay construction.

Bleeding may also be associated with a lack of adequate space in the mix for the asphalt cement. If the VMA content and air void content of the mix do not provide enough room for the binder material, bleeding can occur as the mix is densified by traffic, both shortly after construction and later. The traffic compaction process will decrease the air void content of the mix and may, in turn, squeeze some of the asphalt cement out of the mix. The "extra" asphalt will appear as a longitudinal streak or fat spot throughout the length of each wheelpath.

One additional possible cause of bleeding is the condition of the pavement layer on which the new mix is placed. If the underlying layer has excess asphalt on its surface or excess crack seal material in the cracks and joints, some of this material may be drawn up through a thin new mix layer. Further, if too much tack coat is applied to the original pavement layer, the excess material may be pulled up through a thin overlay and contribute to the bleeding problem.

Solutions

Variations in the asphalt mix temperature behind the paver indicate that the moisture content of the mix may also be variable. Where moisture has evaporated, the temperature is lower. This latter phenomenon can contribute to both the bleeding of the mix later under traffic and the generation of fat spots in the mix during construction. It is important, therefore, that the aggregate used in the mix be relatively dry and that the moisture content of the mix upon discharge from the asphalt plant be as low as possible, but not more than 0.5 percent. Extra care needs to be taken in drying when producing mixtures that incorporate highly absorptive aggregate.

Bleeding problems caused by excess asphalt cement in the mix can most easily be solved by reducing the asphalt content, consistent with other properties of the mix, such as air voids, VMA, and strength or stability. Bleeding problems that occur in conjunction with pavement rutting usually can be solved, however, only by a complete redesign of the asphalt mixture, with emphasis on proper air void content and VMA criteria.

Effects on Performance

Occasional fat spots in the mix should not affect the ultimate durability of the pavement to a significant degree. A large number of fat spots or bleeding in the wheelpaths does affect pavement performance, however, because of variable asphalt and air void content in different parts of the mix. In addition, other mix problems, such as shoving, rutting, and loss of skid resistance, may occur in a mix that contains many fat areas or bleeding in the wheelpaths. The design of the asphalt mixture, the operation of the asphalt plant (more complete removal of moisture), or both should be checked to ensure that the mix produced will provide adequate pavement performance under vehicular loading.

ROLLER MARKS

Description

During the compaction process—whether vibratory static steel wheel or pneumatic tire rollers are used—longitudinal creases or marks are left in the surface of the mix. Once the mix has cooled to a temperature range of 70°C to 60°C (160°F to 140°F), these marks are typically removed by the finish roller. Roller marks are indentations that remain in the surface of the mix after rolling has been completed (see Figure 19-10).

Roller marks may also exist in the asphalt surface when any roller is parked on the hot mat for a period of time or when a vibratory roller is vibrated in place. Particularly when used in the breakdown position, pneumatic tire rollers can leave visible longitudinal marks that can still be seen after the finish rolling has been completed. Vibratory washboard marks may be visible if that roller is operated at an improper vibratory amplitude, frequency setting, or speed, as shown in Figure 19-11.

Causes

Roller marks can be an indication that the proper number of roller passes has not been made over the mix (see

FIGURE 19-10 Roller marks in freshly laid asphalt pavement.

FIGURE 19-11 Washboard marks left by improperly operated vibratory roller.

Section 18). If the compaction process is halted before the required amount of rolling has been completed or if the mix cools before the compaction process has been finished, the longitudinal marks or creases made by the rolling process will remain in the surface of the mix.

Roller marks left in an asphalt layer also may indicate a tender mix (see Section 3). The roller operator will normally be unable to remove all the marks left by the compaction equipment if the mix is tender or unstable. A tender mix usually will not support the weight of the finish roller until it has cooled to the point at which the viscosity of the asphalt cement has increased enough to stiffen the mix. By the time the mix has decreased in temperature to this point, however, the required level of density can generally no longer be achieved because the mix has lost its workability. For this reason, the roller marks or indentations left during the breakdown and intermediate roller passes usually cannot be removed during the finish rolling process. All of the asphalt cement, aggregate, and mix properties that contribute to the formation of a tender mix, as discussed above, also contribute to the inability of the finish roller to eliminate roller marks.

Solutions

If the cause of roller marks is inadequate compaction, additional roller passes should be made with the breakdown, intermediate, or finish rollers to properly densify the mix. The solutions for inadequate compaction related to mix design deficiencies all involve changes to the mix design and to the production of the mix at the asphalt plant. Asphalt cement quality and content, aggregate properties and characteristics, and mix temperature all play a significant role in the workability and stability of the asphalt material under the compaction equipment.

Roller marks normally cannot be removed from a tender mix until the mix temperature has decreased to a relatively low level—usually less than 70°C (160°F).

Sometimes it is possible, depending on environmental conditions and the properties of the mix, to remove roller marks left in the mix by using a pneumatic tire roller. If the surface of the mix is hot enough [60°C (140°F) or more], several passes with a pneumatic tire roller can be made to "iron out" the surface of the pavement. Finally, roughness or washboarding caused by incorrect operation of a vibratory roller should be eliminated by using proper operating techniques with this equipment.

Effects on Performance

Roller marks are normally an indication that the proper level of compaction has not been achieved. In terms of ultimate pavement durability, the air void content or density of the mix is the single most important characteristic that governs the performance of the asphalt mixture under traffic. If the air void content of a dense-graded mix is high—the density is too low—the pavement generally will not perform well under traffic.

SEGREGATION

Description

Segregation is the separation of the coarse aggregate from the rest of the mix in an HMA mix. Segregation results from mishandling the mix at any of several points during the mix production, hauling, and placing operations. When segregation occurs in a paving project, it is likely to lead to forms of long-term pavement distress such as wavy surface and poor compaction. It can occur as the mix is delivered from the asphalt plant to a surge silo, as the mix is deposited into the haul truck from the silo, and as the mix is discharged from the truck into the paver hopper. Segregation that is evident behind the paver screed generally takes one of three forms: it may consist of areas of coarse aggregate (rock pockets) that occur randomly across the length and width of the layer; it may occur at a transverse location across the width of the lane (truckload-to-truckload segregation); or it may occur along one side of the paver width (longitudinal or side-to-side segregation).

Causes

The cause of segregation behind the paver is directly related to the type of segregation involved. Rock pockets are generally caused by improper handling of the aggregate in the stockpiles, cold-feed bins, or storage of the HMA at the asphalt plant (see Section 6). They seldom occur when a batch plant is used to produce the mix (without a silo), because the screens and hot bins in the plant recombine any segregated material before it is fed into the pugmill (see Section 8). Further, the pugmill blends all the aggregates together and normally eliminates any segregation that might have occurred previously. If a silo is used on a batch plant, however, the mix may segregate for all the same reasons that affect a mix produced in a drum-mix plant and passed through a surge or storage silo (see Section 11).

Rock pockets and random segregation are occasionally found on the roadway when the mix was manufactured in a drum-mix plant (see Sections 9 and 10). If the loader operator places a bucketful of segregated aggregate in a cold-feed bin, that material can pass through the drum, surge silo, haul truck, and paver without being completely mixed in with the other aggregate. This is because the drum-mix plant operates on a continuous-flow instead of a batch basis. If the aggregate in the cold-feed bins is segregated, that material will show up on the roadway in a random pattern both transversely and longitudinally.

Some mixes are more prone to segregation than others (see Section 3). Asphalt mixes that have large maximum-size coarse aggregate [25 mm (1 in.) or greater], have low asphalt cement content, or are gap-graded will tend to segregate more readily when handled than a dense-graded mix containing optimum asphalt content and a smaller maximum-size coarse aggregate.

Segregation that occurs on one side of the paver (side-to-side segregation) when a batch plant without a silo is used to produce the mix is normally caused by improper loading of the haul truck from the pugmill (see Section 11). If the mix is not loaded in the center of the width of the truck bed, the coarse aggregate particles in the mix may roll to one side of the truck and accumulate along that side. When the mix is delivered to the paver hopper, the segregated mix will be placed on the roadway along the same side, and the segregation will appear as a longitudinal streak on one side of the paver only.

Segregation that occurs on one side of the paver when a batch plant with a silo or a drum-mix plant is used to produce the mix is typically caused by improper loading of the mix into the surge silo (see Section 11). As the mix is deposited into the silo from the conveying device (slat conveyors, belt conveyor, or bucket elevator), the mix is thrown to one side of the silo, and the coarse aggregate particles are separated from the finer materials. When the silo is emptied, the coarse aggregate is deposited on only one side of the truck. This segregated material then passes through the paver and is seen on one side of the mix after laydown. Further, as with a batch plant, if the truck is not loaded in the center of its width under the silo, rolling of the coarse aggregate particles may occur, and longitudinal segregation will then appear on one side of the new mat.

Truckload-to-truckload segregation has many potential causes (see Section 11). The most common is improper loading of the haul truck from the silo. If mix is placed in the truck bed in one drop from the silo, the coarse aggregate particles in the mix have a tendency to run to both the front of the bed and the back tailgate. This rolling of the coarse aggregate is exacerbated if the plant operator continuously opens and closes the silo gates near the end of the truck-loading procedure to ensure that the full weight of mix is placed on the truck.

Some believe that truckload-to-truckload segregation can also be caused by improper discharge of the mix into the silo. Mix that is dribbled into the silo from the conveying device is said to be susceptible to segregation inside the silo. Even if this occurs, the mix that is segregated in the silo will appear only as random rock pockets in the layer behind the paver, instead of in a systematic manner between truckloads of mix delivered to the paver. Thus it is doubtful that any segregation of the mix that occurs during the continuous process of loading the silo will appear on the roadway in a discontinuous pattern—only at the beginning or the end, or both, of a truckload of mix.

Temperature segregation of the mix has also been shown to be a problem. The mix cools more quickly near the edge, bottom, and top of the truck during haul. This cooler material is not always remixed with the hotter HMA, leading to temperature segregation during the laydown operation. The result can be more variability in density during construction and a nonuniform surface. This problem can be monitored by infrared technology.

Solutions

The solution to each type of segregation is related to its cause. For random rock pockets that appear intermittently in the mat, the method of stockpiling the coarse aggregate at the asphalt plant and the charging of that material into the cold-feed bins by the front-end loader should be checked to ensure that proper aggregate handling techniques are used. Further, all points in the mix-production system at which coarse aggregate particles might accumulate should be inspected to determine whether the flow of the coarse and fine aggregate pieces is uneven. A batcher should be used at the top of the silo to direct the mix into the center of that piece of equipment.

For longitudinal (side-to-side) segregation, the loading of the haul truck from the batch plant pugmill or from the silo at either the batch or drum-mix plant should be monitored to ensure that the mix is being delivered into the center of the width of the vehicle. When a drum-mix plant is used to manufacture the mix and the segregation always appears on one side of the paver, several trucks should be loaded at the silo while facing in the opposite direction from their normal loading procedure. When the mix is passed through the paver, the longitudinal segregation should change sides—go from one side of the paver lane to the other. If the transverse position of the longitudinal segregation does change (and it should), the solution to the side-to-side segregation problem must take place at the top of the silo. The mix deposited into the silo from the conveying device must be directed into the center of the silo instead of to one side, so that the coarse aggregate particles in the mix are not thrown to only one side of the silo. This solution requires some changes in the configuration of the equipment at the top of the silo. If the transverse position of the longitudinal segregation does not change, the segregation is probably caused by a paver problem.

Most truckload-to-truckload segregation can be reduced significantly by using multiple drops of mix to load the haul trucks. If a tandem-axle truck is being loaded, at least three different drops of mix should be made—into the front of the truck near the front bulkhead, into the back of the truck near the tailgate, and into the center of the truck bed between the first and second drops. If a larger truck is used, additional drops of mix should be made—the first into the front of the truck bed and the second near the tailgate. One of the main solutions for truckload-to-truckload segregation is to minimize the distance the coarse aggregate particles can roll. This is accomplished by making multiple drops of mix into the truck.

The plant operator should be prohibited from topping off the load of mix at the end of the loading process. Each time the silo gates are opened and a little bit of mix is dribbled into the truck, the coarse aggregate particles will tend to separate from the finer material. This problem can be eliminated only by preventing it from occurring.

If segregation does take place during the loading of the truck and there is an accumulation of coarse aggregate particles at the tailgate of the truck, at the front of the bed, or both, the amount of segregation that appears on the roadway can usually be reduced by proper unloading of the haul truck at the paver. First, the truck bed should be raised a short distance, before the tailgate of the truck is opened, so that the mix can shift in the bed and slide against the tailgate. This procedure surrounds any coarse particles that have rolled to the tailgate area with nonsegregated mix. Instead of only the coarse aggregate being deposited first into the paver hopper, a mass of mix is discharged when the truck tailgate is opened, flooding the hopper with mix and typically incorporating the segregated coarse aggregate into that mass of HMA mix.

The operation of the paver can also increase or reduce the amount of segregation that occurs behind the screed. If the paver hopper is emptied of mix, if the slat conveyors are visible, and if the wings of the hopper are dumped after each truckload of mix, any coarse aggregate particles that have collected at the tailgate of the next truckload of mix will be deposited into the bottom of the hopper and then carried directly back to the empty auger chamber in front of the screed. This segregated material will appear behind the screed as soon as the paver moves forward. This transverse segregation, therefore, does not really occur at the end of the truckload, but rather at the beginning of the next truckload of mix.

Segregation can be reduced by keeping the hopper full of mix between truckloads. The mass of mix that floods the hopper from the haul truck will be blended with the mix already in the paver hopper. Any segregated material will be further incorporated in the mix that is pulled back to the augers by the slat conveyors and passed under the paver screed. The amount of truckload-to-truckload segregation can be decreased significantly, but not always eliminated completely, by good paver operating techniques. The problem should really be solved during the truck-loading procedure.

The use of MTVs has also shown some benefit in reducing segregation. The MTV remixes the HMA, and this reduces aggregate segregation, as well as differential temperatures within the mix (also known as temperature segregation).

Effects on Performance

Segregation can affect pavement durability directly by increasing the air void content of the mix in the segregated areas and increasing the potential for moisture damage. Further, the segregated locations are very susceptible to raveling and, if bad enough, to total disintegration under traffic. Segregation, whether in the form of rock pockets, longitudinal (side-to-side) segregation, or transverse (truckload-to-truckload) segregation, is extremely detrimental to the long-term performance of the pavement.

POOR MIX COMPACTION

Description

The HMA mixture should be compacted so that the in-place air voids are at an acceptable level. If the air voids are above 7 to 8 percent, the mix will be permeable to air and water and will not have the required durability. If the initial compaction results in air voids of approximately 4 percent or lower, the mix may become unstable under traffic after additional densification; the result will be shoving and rutting of the mixture, as discussed earlier. Most mixes require a significant level of compaction to reach the desired 7 to 8 percent or less air voids.

Causes

When the mix is too stiff or too tender, compaction is difficult. The primary cause of poor compaction is low design mix density (high design air voids) (see Section 3). Other causes include inadequate underlying support (Section 14), improper type and weight of rollers (Section 18), improper tire pressure in rubber tire rollers (Section 18), improper rolling procedure (Section 18), improper mix design (Section 3), mix segregation (see above), moisture in the mix (Section 3), variation in mix temperature, and low mix temperature.

Solutions

Solutions to compaction problems include taking the necessary steps to ensure adequate support, producing an acceptable mixture, and using satisfactory laydown and rolling techniques. When support is inadequate, the compaction requirements may have to be relaxed, or the mix may have to be redesigned to allow for satisfactory compaction.

When the asphalt content is too high, the mix may compact too easily, resulting in low air voids (which leads to rutting; see the earlier discussion). When the asphalt content is too low, the mix may be stiff and difficult to compact to the specified density. A satisfactory mix design will produce a mix with optimum asphalt content that can be compacted with reasonable effort to the required density.

Good laydown and rolling techniques, as discussed earlier, are necessary for good compaction. Density can normally be increased by reducing the speed of the paver or rollers. Density can also be increased by increasing the weight and number of rollers. The compaction process must be adjusted to produce optimum density.

Effects on Performance

When the compaction is inadequate (more than 7 to 8 percent air voids) the mix will be permeable to air and water. Water can flow through the HMA and reduce the strength of the underlying base course. The high voids also result in excessive oxidation of the HMA, which leads to raveling, cracking, and general deterioration of the HMA over a period of time.

When the air voids are excessively low after compaction (less than 4 percent) the mix is likely to rut and shove under traffic. The low voids are the result not of too much compaction, but of an unsatisfactory mixture.

OTHER PAVEMENT PROBLEMS

The above discussion has addressed only those problems that occur at the time of the asphalt mix production, laydown, and compaction. A number of other deficiencies can occur on an asphalt pavement structure with time and traffic loading once construction has been completed. Those distresses include fatigue cracking, rutting, shoving, raveling, and disintegration. A discussion of such distresses is beyond the scope of this handbook.