Accessible Exterior Surfaces

A Review of Existing Test Methods for Surface Firmness and Stability

Phase I Technical Article

Submitted to:

U.S. Architectural and Transportation
Barriers Compliance Board
Washington, DC 20202
Contract No. QA96005001

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26 November 1997

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INTRODUCTION

The Americans with Disabilities Act Accessibility Guidelines (ADAAG) for Buildings and Facilities defines accessible routes in terms of grade, cross slope, and changes in level. These characteristics are easily measured with standard tools and test methods. The Guidelines further state that accessible routes must be "stable, firm and slip-resistant" (Section 4.5.1) (US ATBCB, 1992).

The Access Board's technical bulletin on surfaces lists several devices capable of measuring surface slip-resistance. However, the bulletin does not specify any methods for measuring firmness or stability, nor is any other clarifying information provided in ADAAG on these surface characteristics.

Firm and stable surfaces are easier to cross than soft and unstable ones. A firm and stable surface such as concrete resists change and deformation, which enables more of the energy exerted by a person to be used to move across the surface. A person crossing an unstable surface such as dry sand expends more energy deforming or displacing the surface.

Objective measurement methods are needed to evaluate the accessibility of surfaces and develop guidelines that will provide non-discriminatory access to persons with disabilities. This research project (Phases I and II) seek to identify and develop objective measurement methods for determining surface accessibility. The specific objectives of Phase I of this project were:

1) To provide an overview of solutions available to facilitate access across non-accessible surfaces;
2) To conduct a comprehensive review of existing test methods for firmness, stability and other related material properties; and
3) To make recommendations for the development of a standard test method for measuring surface firmness, stability, and other factors which may be determined to affect accessibility.

METHODS

Information on existing access solutions and test methods were gathered from numerous sources, including books, articles, product literature, reports, patents, standards, experts and databases. All written materials were reviewed, summarized and evaluated with respect to the scope of this project.

SOLUTIONS USED TO COPE WITH "NON-ACCESSIBLE" SURFACES

Various methods were identified which improve outdoor access for people with mobility limitations. These methods were categorized as personal technologies, structural alternative surfaces, soil stabilizers, or alternative surfaces for playground access.

Personal Technologies

Personal technologies are assistive devices designed to be used by a specific individual. These technologies, which include canes, crutches, wheelchairs and walkers, are typically purchased and maintained by one user. As a result, these products increase access only to individuals who have them.

Typically, canes, crutches and walkers are modified with special tips to enable users to negotiate unstable or soft surfaces. Examples include a spike for cane tips that increases stability on snow and ice, and a cane with offset legs that improves traction on uneven terrain.

A few wheelchair accessories have been designed to improve wheelchair performance on specific terrain such as sand or rough ground. These consist of exceptionally large wheelchair tires for sand, and knobby tire treads for off-road surfaces. Add-on power units can also improve access to rough terrain when combined with the appropriate off-road tire.

Alternative manual and powered wheelchairs have been designed to negotiate rough terrain. The alternative wheelchairs included a rickshaw-style cart with balloon tires for sand, a four-wheeled mountain bike type wheelchair with hand brakes, and a powered wheelchair with wider tires and a low center of gravity for increased stability. While these alternative wheelchairs improve access to specific environments, there were no models that were capable of accessing a wide variety of surfaces, including grass, gravel, ice, mud, and sand.

Structural Alternative Surfaces

Structural alternative surfaces, such as mats and grid systems, offer universally usable and less costly options for accessing beaches and trails. Portable alternative surfaces include mats and mesh grids designed to be laid across sand or snow to form an accessible path for wheelchair users. While portable surfaces facilitate access, they are best used for traveling short distances and force wheelchair users to rely on assistants to position them on the surface. Non-portable alternative surfaces include plastic grid systems that provide more structure to surfaces such as grass, gravel or dirt, improve surface stability and firmness, and preserve the natural look of the surface. Non-portable alternatives improve access for many people to specified areas, but also restrict the user's movement to particular locations.

Soil Stabilizers

Soil stabilizers include both traditional paving products and soil additives. Traditional paving products replace existing surfaces. These include soil cements, hot and cold mixes, and clay-aggregate mixes. While they visually alter the trail and often require large mixing tools, these products have traditionally been the most effective stabilization agents. Soil additives are designed to bind with existing trail materials to produce firmer and more stable surfaces. Surface binders / additives include substances such as clay fillers, enzymes, ground seed hulls, lignins and tree resin emulsions. Many stabilizers do not visually alter the appearance of the site, and can be hand-mixed for use on trails that are difficult to access with large equipment.

Alternative Surfaces for Playground Access

Surfacing materials used under and around playground equipment should enable access while cushioning impacts due to falls. Alternative playground surfaces include engineered wood fiber, shredded rubber, and rubber mats. These surfaces provide various levels of access and safety which are dependent upon the depth of the material. Some of the disadvantages to using these surfaces include high maintenance or installation costs.

REVIEW AND EVALUATION OF EXISTING TEST METHODS

In conducting the literature review, all test methods that measured surface firmness or stability were analyzed for their suitability to measure a wide variety of surfaces. In addition, the methods were evaluated in terms of accuracy, resolution, repeatability, reproducibility, range, experience required, time required, availability, cost, and whether the test could be performed in the field or required a laboratory setting. Each test method identified was grouped into one of six categories based on the technique used to measure the material. These categories were: penetration, torque, rolling resistance, work measurement, physiological response, and water content.

Penetration Test Methods

Surface firmness is the degree of surface resistance to deformation, especially by indentation or the movement of objects. Penetration tests measure surface firmness, which is a major factor affecting surface accessibility. For example, a person walking on a firm wooden floor will not leave footprint indentations, because the wood resists deformation. The same person walking on soft soil will indent the surface and leave footprints, because the soil is not firm.

Four different types of penetration tests were found: physical, impact, compression, and non-invasive.

Physical Penetration Test Methods

Physical penetration tests involve gradually piercing or indenting a section of the sample with a probe. There are two types of physical penetration tests. In one type, a force of known magnitude is applied to a surface, and the amount of displacement caused is measured. An example of this type of test is the cone penetrometer. In this test, a tip in the shape of a cone is pushed into a surface with a known amount of force and the distance the tip travels into the surface is measured.

The second type of physical penetration test measures the force required to cause a specified amount of surface deformation. An example of this type of test is the pocket penetrometer, where a probe tip is inserted a given depth into the surface and the amount of force required to cause the penetration is measured. Numerous standard and nonstandard physical penetration tests are used to measure the firmness of many different substances, including soils, building materials, foods, and foams.

Physical penetration tests have been used to measure the firmness of a wide range of objects with a high degree of accuracy and are likely adaptable to many types of surfaces. Many of the test procedures for physical penetration test are simple, require very little time per trial, and provide quick results. However, the sizes and shapes of the probes and test devices used are specifically designed to test particular surfaces; a technician must be experienced and highly skilled to select the correct device for each material and to obtain an accurate measurement. In addition, the nature of probe testing only permits data to be collected on selected spots rather than continuously across a surface. Sites with variable surface firmness, such as along outdoor trails, would be difficult to test with a physical penetration method. Penetration tests are also most accurate when performed in a laboratory setting, where factors that significantly affect test results, such as temperature, moisture content, and surface profile, can be controlled or monitored. However, the number and types of surfaces that can be tested in the laboratory are limited to surfaces such as carpet that can be sampled or reconstructed accurately.

Impact Penetration Test Methods

Impact tests measure a material's ability to withstand loading that occurs over a very short period of time. There are two types of impact penetration test methods, grouped by the body delivering the impact force. One type measures the forces applied by the sample to the measurement device. An example of this type of test uses sensors attached to the rubber tips of canes or walkers. The sensors measure pressure as a person crosses a surface with the instrumented cane or crutch.

The other type of impact test involves dropping a standard object onto a surface and measuring the impulse forces experienced by the object. An example of this method is a playground surface test where an instrumented device is used to impact the test surface and measure acceleration characteristics over time.

Impact devices designed to be dropped onto the surface would be appropriate to test non-portable surfaces. However, such tests require smooth surfaces for accurate readings and cannot be used on irregular outdoor surfaces. Impact test methods would also be unable to measure the firmness of surfaces that deform slowly over time. An example of such a surface is viscoelastic foam, which would register a very firm rating in an impact test but deforms in response to force applied over a longer period of time.

Compression Penetration Test Methods

Compression tests measure the resistance to a load delivered evenly to an entire surface sample. Compression tests typically involve pressing a flat plate onto a sample surface and measuring any changes in sample height.

There are many standard compression tests that are used to measure the firmness of substances including soils, building materials, foam, carpet, and foods. A few nonstandard compression tests were found that measured the firmness of body tissues such as breasts and scars. These tests typically used the weight of the device to compress the sample, and firmness was determined by the area compressed or the length of a spring probe.

Compression tests that use the weight of the test device to deform the sample are easy to perform and require very little training. These tests can produce an accurate, objective measure of firmness. However, compression tests require the test apparatus and method to be optimized for the specific firmness range of the sample. The measurement range of all compression testing devices found was very limited. Most standard soil compression tests are conducted over several days and specify that loads of thousands of pounds be placed on the sample with heavy, expensive machinery. The weight of the load and the long testing time make these methods impractical for surface accessibility testing. Testing devices as complex as the fatigue stomper require specialized training to operate.

Non-Invasive Deformation Penetration Test Methods

Non-invasive deformation tests apply non-invasive forces or passively measure deformation characteristics. These tests do not permanently deform the structure of the material tested but instead measure temporary deformation characteristics.

An example of a non-invasive deformation test is a holographic imager which shines split laser beams on structures such as rotating propellers. Areas of significant material vibration are highlighted on the holographic film plate used to record the test. Non-invasive deformation tests using radar refraction, sonic vibrations, and holographic imaging to analyze deformation were found. Non-invasive deformation test methods were applied to a wide variety of materials, including soils and moving machinery parts.

Non-invasive deformation tests provide very sensitive measurements of surface deformation characteristics without puncturing or marring test surfaces. However, the equipment required to perform these tests is expensive and requires significant technical expertise to operate correctly. In addition, radar and holographic imaging systems do not provide quantitative measurements but instead return relative data that cannot be accurately correlated to results from other samples.

Torque Test Methods

Torque tests measure shear strength, which can be considered a direct measure of stability. Stability is considered a measure of a surface’s ability to resist sudden change in position when a multi-directional force is applied.

Torque tests measure the degree of resistance to turning forces. An example of a torque test device is the shear vane meter. The device measures the amount of force required to twist sharpened vanes through soil. The resistance to the vanes is caused by chemical and frictional forces causing the soil particles to cohere, or stick together. The more the particles can cohere, the greater the soil's shear strength.

An additional method to measure the shear strength of soil uses a tractor tire to apply torque. The amount of force required for forward motion is measured by a dynamometer. Another method that measures the torque experienced by a wheelchair wheel tracked the revolution rates of the wheelchair wheels and treadmill rollers. Torque values for this method were estimated mathematically.

Torque testing was the only method found that was capable of providing a reliable measurement of surface stability. The shear vane meter torque test is simple to use and does not require extensive operator training or experience. However, shear strength testing cannot be applied to all materials. For example, the particles in granular materials such as sand and gravel do not cohere well. The strength of these materials comes from their ability to resist shear by flowing around the cutting planes of the testing device. As a result, granular materials register as being quite stable in soil tests, but in reality are highly inaccessible because they flow around and impede the movement of wheels, feet, and crutch tips. In addition, all torque tests are only capable of spot testing, and cannot provide continuous information about changes in stability that occur over long distances.

Rolling Resistance Test Methods

Rolling resistance is the amount of friction or other resistance inhibiting the rolling motion of an object. For example, it is more difficult to roller-skate on a rocky trail surface than on a smooth wood floor because the rough surface of the trail generates much friction against the skate wheels.

Two types of test methods were found that measure rolling resistance. One test method measures the distance an object rolls with a given amount of energy. An example of this type of test is the stimpmeter, where an object such as a golf ball is given energy by being positioned at the top of a ramp, and the distance the golf ball travels on the surface after being released is measured. The rolling resistance of the surface is correlated to the distance the object traveled across the surface.

The other rolling resistance test method measures the amount of energy required to move a surface past an object. An example of this type of test is a wheel placed on a revolving drum covered with a sample surface. The amount of power required to rotate the drum is proportional to the rolling resistance of the surface.

These types of tests were used to measure the rolling resistance of a wide range of surfaces, including carpet, gravel, sand, soil, turf, and other artificial surfaces.

Rolling resistance test devices such as the stimpmeter are inexpensive, require little training to use, and provide good relative measures of surface firmness and stability that can be performed on virtually any surface. However, the results they provide are estimates of actual rolling resistance because a constant velocity is assumed for the rolling body. If the test is performed with a wheelchair and rider, the rider's mass and weight distribution significantly affect the results. In addition, stimpmeter tests cannot be conducted on sloped surfaces because the energy given to the rolling object varies with the grade of the slope.

Work Measurement Test Methods

Several studies correlated the amount of work required to cross a surface in a wheelchair with surface firmness, stability, and/or overall accessibility. Wheelchair work research measured the work required to propel a wheelchair a given distance. The work required to cross a given surface is constant, no matter who crosses the surface. For example, a strong, young, physically fit person would expend less energy than an older, frail individual with quadriplegia to propel a standardized wheelchair across a given surface, but both people would perform the same amount of work.

Two types of tests were used to measure wheelchair work. One method requires a rider to initiate wheelchair movement across an instrumented platform that measures the direction and magnitude of forces exerted. Acceleration and velocity are also measured. This method requires complex calculations and significant assumptions to be factored into the analysis.

The other method used the SMART^{Wheel}, an instrumented wheelchair wheel capable of measuring propulsive forces applied to the pushrim as the wheelchair was propelled a given distance. This method permits assessment of surface accessibility over long distances. It also takes into account the work required to propel a wheelchair across irregularly sloped surfaces. The wheelchair work measurement method is conducted with a standardized wheelchair and rider set-up, and provides a direct indication of surface accessibility. However, the equipment required for the wheelchair work measurement method is expensive, not yet commercially available, and training is required to conduct the testing.

Physiological Response Test Methods

Physiological response tests measure the physiological energy costs of crossing a surface. The most common parameters measured in these tests include measurements of heart rate, oxygen metabolism, carbon dioxide evolution, and lung tidal volume to determine physiological energy expenditure.

Physiological response test results provide a definitive, though very relative, measurement of accessibility. Because such tests are usually performed in a laboratory setting, factors such as surface profile, humidity, temperature, and surface moisture content can be controlled. Results from repetitive evaluations can determine accessibility for populations similar to those represented by the test subjects. However, each test condition must be retested on each subject several times to ensure that accurate data is obtained. Sufficient numbers of representative users must be tested to provide conclusive results for a heterogeneous population. Also, physiological response tests are highly dependent upon the age and physical fitness of the subjects. Testing and analysis equipment is extremely expensive and trained personnel are required to ensure safe and proper equipment operation.

Water Content Test Methods

While water content testing does not provide a direct measure of surface accessibility, water content directly affects surface density, firmness, and stability. In addition, the freeze / thaw action of water accelerates surface degeneration. Water content testing should be performed when assessing the accessibility of many surfaces. On surfaces where water content is variable, data should be collected over the range of moisture expected over the seasonal progression. Water content testing may also indicate the suitability of various access improvements. For example, a soil treatment may work well in desert soils but not in swampy areas or wet climates.

Several standard water content tests were found. One water content test type uses two probes to measure the electrical resistance of soil, which is roughly proportional to its water content. Any resultant changes in mass are attributed to the loss of water in the sample. Such tests are rapid and fairly accurate, but cannot be conducted on hard surfaces because of the difficulty of inserting the electrodes.

A standard method of water content testing directs high-energy neutrons into the sample; the proportion of neutrons slowed by water in the sample is detected by a counter and correlated to water content. This method involves the risk of handling nuclear material, requires extensive training to perform safely and accurately, and loses sensitivity in soils with large rocks.

Another standard method, widely used for its accuracy and reliability, is the dry weight method. In this method, a surface sample is weighed, then heated in an oven until its weight no longer changes. Although the drying period can be long, and must take place in a laboratory, this method is simple to perform and very accurate.

CONCLUSION

This comprehensive information review found that most of the existing test methods were specifically designed to measure a particular type of material or surface, and are incapable of reliably measuring the wide range of surface types found outdoors.

Only the wheelchair work measurement method shows potential to be developed into a standard for determining whether a given surface is sufficiently firm and stable to be considered accessible under the Americans with Disabilities Act (ADA). This method determines the amount of work required to propel a standardized wheelchair across a surface, and thus provides information about its accessibility. This method can accurately assess a wide range of surface types.

Another test method that utilizes the portable tire penetrometer prototype could potentially be developed into a standard test method for determining surface firmness. However, this tool requires further refinement and is not yet commercially available.

The Wheelchair Work Measurement Method

The wheelchair work measurement method determines the amount of work required to propel a wheelchair across a given surface in a straight path and through a turning maneuver. It simulates a real-world condition and provides information about the overall accessibility of the surface, including its firmness, stability, texture, and slope. Although currently a provisional standard for playground surfaces, this method shows promise as a national standard for all outdoor surfaces if two problems can be resolved. First, the equipment required for this test should be made more portable. Second, the percentage of the population that can perform a given amount of work should be determined so that reasonable minimum performance criteria or appropriate level of access specifications can be determined.

Need for Portable Tools

In order to successfully implement an accessibility standard for exterior surfaces, the measurement devices must be easy to use, portable, and readily available. Beneficial Designs is developing simple, portable devices to measure surface accessibility, primarily surface firmness and stability. Measurements obtained with these portable devices will be correlated with the work required to propel a wheelchair across the surface. This work is funded by the National Center for Medical Rehabilitation Research in the National Institute of Child Health and Human Development at the National Institutes of Health through a Small Business Innovation Research Phase II grant.

Energy Consumption and Human Subject Testing

The human body cannot work at 100% efficiency; all the energy a person expends to cross a surface is not translated into forward motion. Efficiency differs by anatomy, physical fitness, type of disability, and other factors.

Human subject testing needs to be conducted to estimate the percentage of the population capable of performing a given amount of work, and whether wheelchair work measurements can indicate the level of access experienced by the individual user.

The rate of energy consumption can be measured as persons walk or wheel across different types of surfaces. Study subjects should span a variety of ability groups, because each group has a different level of physiological efficiency. In addition, the subject group should have gender, ability, fitness, and other characteristics representative of the general population so that the study results can be generalized to provide information about a larger population.

Participants in this study should perform standard tests for strength and endurance so that their level of fitness relative to published values for other populations can be determined. Results from such a study could predict the percentage of the population expected to perform a given amount of work, as well as the range of energy consumption required by a variety of users to cross surfaces.

REFERENCE

United States Architectural and Transportation Barriers Compliance Board (Access Board) (1992): “Americans with Disabilities Act Accessibility Guidelines for: Buildings and Facilities, Transportation Facilities, Transportation Vehicles,” US ATBCB, Washington, DC.

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