A REVIEW OF THE DESIGN AND CONSTRUCTION OF MASONRY NOISE BARRIER SYSTEMS

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ABSTRACT

Noise barriers are wall panels placed on the sides of highways to block traffic noise from intruding into the adjacent residential areas. Masonry noise barriers are among the most commonly used noise barrier systems due to the availability of masonry, its ease of construction, efficient acoustic performance, and desirable aesthetics. Masonry also has sufficient capacity and durability to resist out-of-plane loads and long term exposure to weather conditions. The main criteria for the design of masonry noise barriers outlined in existing design codes and guidelines include loading, acoustic performance, durability, and aesthetics. Nowadays, a new generation of polymeric masonry units has been used in noise barrier systems to improve speed and ease of construction and acoustic performance of the barriers. The key advantage of these novel masonry units is their light weight, which makes them easy to handle on site. However, the structural design of these newer masonry noise barrier systems has not been adequately addressed in the current design codes and guidelines. Existing provisions in the design codes need to be revised to accommodate new technologies. In this paper, current requirements for the design of masonry noise barriers are reviewed and examples of novel masonry noise barrier systems are presented.

KEYWORDS: noise barriers, sound walls, polymeric units, durability

INTRODUCTION

Noise barriers are installed at the sides of the highways to reduce the intrusion of the traffic noise into adjacent public areas [1, 2]. Compared to other noise barrier systems, masonry noise barriers are superior in noise attenuation, aesthetics, and durability. Thus, masonry has widely been used in the construction of various noise barrier systems. Masonry noise barrier systems designed and constructed in accordance with applicable codes and standards are resistant to inclement weather conditions such as freeze-thaw cycles and prolonged exposure to moisture and sunlight.

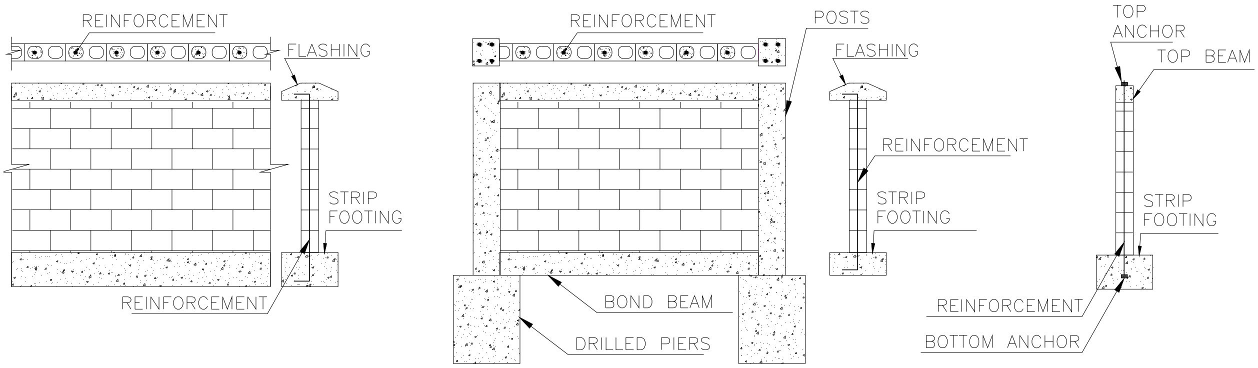
Different design criteria for masonry noise barriers, made of clay or concrete masonry units (CMU), are given in a few design codes and guidelines such as the FHWA Highway Noise Barrier Design Handbook [1], Highway Design Manual by the California Department of Transportation [2] and Guide Specifications for Structural Design of Sound Barriers by the American Association of State Highway and Transportation Officials (AASHTO) [3]. These design documents include the loading, durability, aesthetic, and acoustic requirements for the design of masonry noise barrier systems.

The structural design guide on sound barriers by AASHTO [3] adopts a working stress design approach for the structural design of masonry noise barriers, while other design codes refer to the local masonry design codes and standards, such as the Canadian standard for design of masonry structures (CSA-S304.1-04) [4] or Building Code Requirements and Specification for Masonry Structures by the Masonry Standards Joint Committee (MSJC) [5]. However design codes and guidelines are lagging behind in providing guidance for the structural design of modern masonry noise barrier systems made of novel materials such as polyurethane units. Therefore, the design and construction of these recent noise barrier systems have yet remained proprietary.

In this paper, an overview of the different masonry noise barrier systems is presented. The requirements of current codes and guidelines for the design and construction of these systems are reviewed, and their shortcomings in addressing recent noise barrier systems are discussed.

MASONRY NOISE BARRIER SYSTEMS

Masonry noise barrier systems are constructed as cantilever walls, post-and-panel system, or post-tensioned panels as shown in Figure 1. Cantilever masonry noise barrier systems are supported by strip footing alone, and their stability under transverse loads is maintained by their own weight [2, 6]. In the cantilever system, the masonry noise barrier wall is connected to the foundation by vertical steel bars that pass through the cores of the masonry blocks, which are then filled with grout. Minimum horizontal reinforcement is placed on the bed joints to control mortar shrinkage [6]. Since this system rests on a strip foundation, differential settlement and frost heaving should be taken into consideration [3]. Due to large out-of-plane bending moments at the foundation level, the cantilever system is cost effective up to 5.0 m height [6]. Unlike post-and-panel noise barrier systems, cantilever noise barriers have a smooth surface without any protrusions, which makes it aesthetically more appealing [6].



a) Cantilever wall b) Post-and-Panel c) Post-tensioned

Figure 1: Common Types of Masonry Noise Barrier Systems.

Post-and-panel noise barrier systems consist of masonry panels that are supported on their sides by reinforced concrete or reinforced masonry posts, which are founded on either strip footing or drilled piers [2, 6]. In the latter foundation system, the noise barrier panels rest on either a bond beam or a leveling bed to prevent uplifting of the wall by expansive soils, in this case the noise barrier panel behaves like a deep beam under vertical loads. Drilled piers are typically more cost effective than strip footings [6]. Sometimes a bond beam is constructed on top of the masonry wall to support the top of the wall while protecting the masonry wall from water penetration. The foundation and bond beams are typically made of reinforced concrete. Because of the movement joints between the posts and the masonry panels, the panels are deemed to be simply supported on the sides. Based on the support boundary conditions of the masonry panels in this noise barrier system, the structurally optimum panel's width/height ratio can be determined by linear elastic analysis of the panel under transverse loading. The width and height of the panels are commonly between 4.0 to 7.0 m. Due to two-way transverse behavior of the post-and-panel system under out-of-plane loads, both horizontal and vertical reinforcement is required to provide sufficient bending moment capacity.

Both cantilever and post-and-panel masonry noise barrier systems can be prefabricated off site to simplify and increase the speed of the construction process [2, 6]. The strip footings are made of cast-in-place concrete. In prefabricated cantilever noise barrier systems, dowel bars are placed during construction of the foundation and the prefabricated hollow masonry panels are later placed on the strip footing over the dowels and the hollow cores are grouted. In post-and-panel masonry noise barrier systems, after construction of the strip footing, the prefabricated posts are bolted to the foundation and the masonry panels are installed between the posts utilizing tongue-and-groove connections.

Post-tensioned masonry has been utilized in recent noise barrier systems. A series of threaded steel bars or tendons are installed in the cores of the hollow masonry units and are post-tensioned to provide a clamping force to tie the masonry panel down to the foundation [6]. Post-tension rods can also be installed horizontally in post-and-panel masonry noise barrier systems. The post-tensioned rods are anchored in the bond beam at the bottom of the masonry panel and by bearing plates and anchor nuts at the top [6, 7]. The anchor nuts are tightened in place using either a calibrated torque wrench, a hydraulic jack, or with load-indicating washers placed between the nut and the bearing plate. In some proprietary post-tensioned masonry systems, no mortar is used in the joints [6]. About 4% initial and 15-20% secondary stress losses take place in the tendons due to the elastic deformation and long term creep of masonry, respectively.

MATERIAL REQUIREMENTS

The choice of suitable material and noise barrier system depends on the site where the noise barrier is to be constructed. In the design stage, the selected noise barrier system should be efficient in terms of constructability, cost-effectiveness, and acoustic and structural performance. The noise barrier material should also remain durable when exposed to the local climatic conditions. In this regard, masonry noise barriers have proven to be cost effective, easy to construct, and durable in about any region. Certain material requirements should be met to assure durability and structural performance of the noise barriers. These are covered briefly here but are discussed in greater detail in references [6], [8], and [9].

The guidelines by the Highway Innovative Technology Evaluation Center (HITEC) [8] require concrete and fired clay masonry units to be load bearing units in conformance with ASTM C90 [10] and ASTM C652 [11], respectively. The same guidelines also require concrete masonry units to be light weight (less than 1680 kg/m^3) or medium weight (1680-2000 kg/m^3) as classified in ASTM C90 [10]. On the other hand, Klinger et al. [9] suggested that solid masonry units conforming to ASTM C62 [12] could be used in noise barrier systems as long as the units' surface density satisfies the required noise reduction level. However, due to their heavier weight, solid masonry units are not recommended in seismic regions.

The reinforcement used in masonry noise barriers typically consist of deformed bars placed vertically in the cores of the masonry wall, and steel wires (joint reinforcement) placed in bed mortar joints to control mortar shrinkage. The Canadian standard for masonry construction for buildings (CSA-A371) [13] requires a minimum 10 mm mortar or grout cover for hot-dipped galvanized reinforcement, and 50 mm cover for reinforcing bars or wires without corrosion protection. Additionally, the clear distance between the surface of the bar and any surface of the masonry unit should not be less than 6 mm for fine grout and 13 mm for coarse grout [13]. The maximum diameter of vertical bars and joint reinforcement is limited to No. 30 and 5 mm, respectively [13]. Similar requirements are also provided in the MSJC masonry design code [5] and the AASHTO design guide [3]. The latter document also requires every masonry block in noise barriers prone to vehicular collision to be reinforced by vertical bars.

ACOUSTIC REQUIREMENTS

Noise barriers reduce the noise level through Transmission Loss (TL) and Insertion Loss (IL) [9]. The sound transmission loss is a measure of the energy of the sound of a certain frequency incident on the wall surface relative to the sound energy passing through the wall, which is determined as per ASTM E90 [14] in decibels (dB). Sound insertion loss is the noise reduction due to change of sound sightline from the noise source to the receptor when the noise barrier is inserted, assuming no sound transmission through the noise barrier [15]. For comparison of acoustic properties of different noise barrier systems, noise abatement is reported in terms of Sound Transmission Class (STC), which is a numerical rating for interpreting transmission loss and is determined from ASTM E413 [16] by comparing the TL values for sound of frequencies from 125 Hz to 4000 Hz with a reference STC contour [15, 17].

A comparison of the TL values for different materials given in Table 1 demonstrates the superior acoustic efficiency of masonry compared to other materials. Being of greater density, masonry noise barrier systems experience less vibration due to ambient sound waves [15], leading to improved noise abatement. Based on test results, the transmission loss of single wythe masonry walls can be estimated [15] from Eq. 1, where m is the surface density of the masonry wall (kg/m^2) and f_r is the sound frequency.

$$TL = 20\ \log(m.f_r) - 48\,dB \tag{1}$$

The design guide for highway noise barriers [9] requires a minimum 5 dB noise intensity reduction, which is a combination of IL and TL. The guidelines for selection and approval of noise barrier products [18] require the noise barrier panel to have a minimum transmission loss of 23 dB, when tested according to ASTM E90-04 [14], using the typical truck noise spectrum and having vibration-free joints and fittings. The same guidelines also require the Noise Reduction Coefficient (NRC), a measure of the sound energy absorbed by the wall surface, for absorptive noise barrier materials to be at least 0.7 when measured in accordance with ASTM C423-08 [19]. Any material with minimum TL of 10 dB greater than the noise reduction due to insertion loss may be used in noise barriers since the governing noise reduction mechanism in this case would be the diffracted sound path from the noise source to the receptor [20].

Table 1: Transmission Loss for Different Materials [20]

Material	Thickness (mm)	Surface Density (kg/m^2)	Transmission Loss (dB)
Concrete block 200x200x400mm, lightweight	200	151	34
Dense concrete	100	244	40
Light concrete	100	161	36
Brick	150	288	40
Steel, 18 ga	1.27	9.8	25
Aluminum sheet	3.18	8.8	25
Plywood	25	16.1	23
Polycarbonate	8-12	10-14	30-33
Poly(methyl methacrylate) (PMMA)	15	18	32

STRUCTURAL REQUIREMENTS

The loads that should be considered in the structural design of masonry noise barriers are dead, wind, seismic, vehicular impact, ice and snow, and earth loads. The dead load includes the weight of the noise barrier and all other traffic components that are attached to it [3]. Due to the high compressive capacity of masonry materials, compressive stresses due to dead loads do not govern the structural design of masonry noise barriers.

In non-seismic regions, wind pressure is the governing load in the structural design of masonry noise barriers, which should be applied uniformly on the surface of the noise barrier and its resultant force should be applied at the mid height of the posts. The Canadian standard for certification of noise barriers (CSA Z107.9-00) [21] refers to the Canadian Highway Bridge Design Code (CAN/CSA-S6-06) [22] for structural design of noise barriers and suggests the following equation for calculating the out-of-plane wind pressure on the noise barriers.

$$F_d = q\left(C_e C_d C_g\right) \tag{2}$$

where, F_d is the wind load, q is the reference wind pressure for 25-year return period based on Table A3.1.1 of CAN/CSA-S6-06 [22], C_e is the exposure factor (equal to 1.0 for wall heights up to 10 m), C_d is drag coefficient (equal to 1.3 for a surface with large length-to-height ratio), and C_g is the gust coefficient (equal to 2.5 for noise barriers). AASHTO design guide [3] provides the following equation for computing the wind load.

$$P = 0.04733(1.3V)^2 C_d C_c \tag{3}$$

where, V is the wind speed (km/h) based on 50-year mean recurrence interval, C_d is the drag coefficient (equal to 1.2 for noise barriers) and C_c is a coefficient for combined effects of height, exposure and location, provided in Table1-2.1.2 of that document. The 1.3 factor in equation 3 is to account for gusts. AASHTO design guide uses a wind with higher recurrence interval, but lower drag coefficient and gust factor than the Canadian standard CAN/CSA-S6-06 [22]. Wind pressure at any elevation Z can be calculated according to AASHTO LRFD Bridge Design Specifications [23] using the following equation.

$$P_D = P_B \left(\frac{V_{DZ}}{V_B} \right)^2 \tag{4}$$

Where, P_D is the design wind pressure, P_B is the base wind pressure (equal to 0.0019 MPa for large flat surfaces), V_B is the base wind velocity of 160 km/hr at 10 m height, and V_{DZ} is the design wind velocity at the design elevation Z. V_{DZ} depends on the reference wind velocity V_{10} at 10 m height at the noise barrier location, established from either basic wind speed charts in ASCE 7-05 [24], or site specific wind surveys.

The National Cooperative Highway Research Program (NCHRP) suggested [25] modifications to the provisions of the AASHTO LRFD Bridge Design Specifications for determining V_{DZ}, proposing a 75-year return period for the design wind load by multiplying the wind speed by 1.07. The design wind velocity depends on the sparseness of the structures around the noise barrier location, which should be accounted for.

Seismic forces should be applied uniformly over the surface of the masonry noise barrier wall panel. For post-and-panel systems, the resultant seismic forces on the posts are applied as a concentrated load at 0.7 times the height of the post [25]. The AASHTO design guide [3] provides Equation 5 for the seismic load effect on noise barriers:

$$E = A\,f\,D \tag{5}$$

where, D is the dead load of the noise barrier, A is the acceleration coefficient of the noise barrier site, and f is the dead load coefficient provided in the AASHTO design guide. The AASHTO LRFD Bridge Design Specifications [23] provides the following equation for the elastic seismic response of the m^{th} mode.

$$C_{sm} = \frac{1.2AS}{T_m^{\;2/3}} \leq 2.5A \tag{6}$$

Where, A is the peak horizontal ground acceleration ratio based on the earthquake with 475-year return period, S is the site coefficient based on the soil type, T_m is the period of the m^{th} vibration mode. The Canadian standard CAN/CSA-S6-06 [22] adopts the same equation for seismic load except that A is replaced by AI, where I is the importance factor. The elastic response of the noise barrier is then divided by R, the ductility factor. In these design documents, I and R factors are only defined for different bridge types, not for noise barriers. The National Building Code of Canada [26] provides a ductility factor of 2.5 for concrete and masonry fences taller than 1.8 m, which is a reasonable value to be applied to noise barriers.

If the noise barriers are to function as traffic barriers as well, the AASHTO LRFD Bridge Design Specifications and the Canadian code CAN/CSA-S6-06 require the traffic barriers to be crash tested in full scale, unless the performance of the traffic barrier system has been proven to be adequate based on similar existing traffic barriers. In this test, a test vehicle is accelerated to a specified speed and crashed into the barrier at a specified angle [27]. However, if a noise barrier is mounted above a crash tested (crashworthy) traffic barrier or located less than 1.2 m from a crashworthy traffic barrier, NCHRP provides [25] a minimum vehicular impact load and its point of application on the noise barrier, which eliminates the need for performing a costly and time-consuming, full-scale crash test. For noise barriers prone to vehicular collision, the connection between the noise barrier panels need to be designed to accommodate for the relative displacement between the wall panels [25].

Noise barrier wall panels are required to resistant impact loading due to flying debris and projectiles thrown by passing vehicles [8]. The impact resistance of the panel is determined according to ASTM E695 [28], in which a loading bag is dropped from different heights to the middle of the panel specimen. The height and weight of the bag are as required by the local design code. For example, Florida Department of Transportation [29] requires the noise barriers to be resistant against a 4.5 kg bag dropped from 0.91 m when tested according to ASTM E695.

In cold regions, the weight of ice accumulation on the noise barriers should be accounted for. The Canadian standard CSA Z107.9-00 [21] requires ice accumulation to be considered on one side of the noise barrier panels and two sides of the top beams and flashings. The design thickness of the accumulated ice in different regions of Canada is provided in CAN/CSA-S6-06. Foundations of noise barriers are required to either extend below the frost line to minimize seasonal movements of the walls, or be designed against heaving forces of the soil [3].

GEOMETRY AND LOCATION REQUIREMENTS

Masonry noise barriers are required to meet height, length and location requirements to assure efficient noise abatement without disrupting the aesthetic view of the area where the noise barrier is to be constructed. CALTRANS highway design manual [2] and the AASHTO design guide [3] recommend that noise barriers be located just inside the right of way, otherwise they should be placed farther than 3.0 m from the traveled way and be either shielded by traffic barriers or designed against vehicular impact. Additionally, at the inside of road curves and near gore areas, a piece of paved land between areas where a ramp merges into an existing traffic lane, the horizontal distance should be sufficient to allow the road users to have a proper sight of the road ahead. When located near a gore area, the noise barrier is required to begin or end at least 61.0 m from the theoretical curb nose [2, 3].

In order to meet the acoustic requirements, masonry noise barriers should have minimal gaps. CALTRANS highway design manual [2] requires the noise barriers to be high enough to intercept the noise sightline from the exhaust stack of trucks (assumed to be 3.5 m above the pavement) to the receptor (assumed to be 1.5 m above the ground). Noise barriers are not required to provide noise reduction for more than one story of the adjacent buildings, unless the required increase in height would provide a minimum 5 dB noise reduction for the adjacent residences in a cost-effective manner [2]. Design codes limit the height of the noise barriers to 4.9 m when located farther than 4.6 m from the traveled way, otherwise the aesthetic impact of the noise barrier on the surrounding area due to its excessive height should be considered.

The length of masonry noise barriers should be enough to provide required noise reduction for the end residences, which can be determined by the California Traffic Noise Analysis Protocol [30]. Sometimes, it is more cost effective to build a section of the noise barrier perpendicular to the highway after the end dwelling [2]. Where access to the highway through the noise barrier is provided with overlapping parallel sections, the length of the overlap should be at least 3 times the offset distance between the overlapping parallel panels [2, 9] to maintain the integrity of the acoustic performance of the noise barrier.

DURABILITY REQUIREMENTS

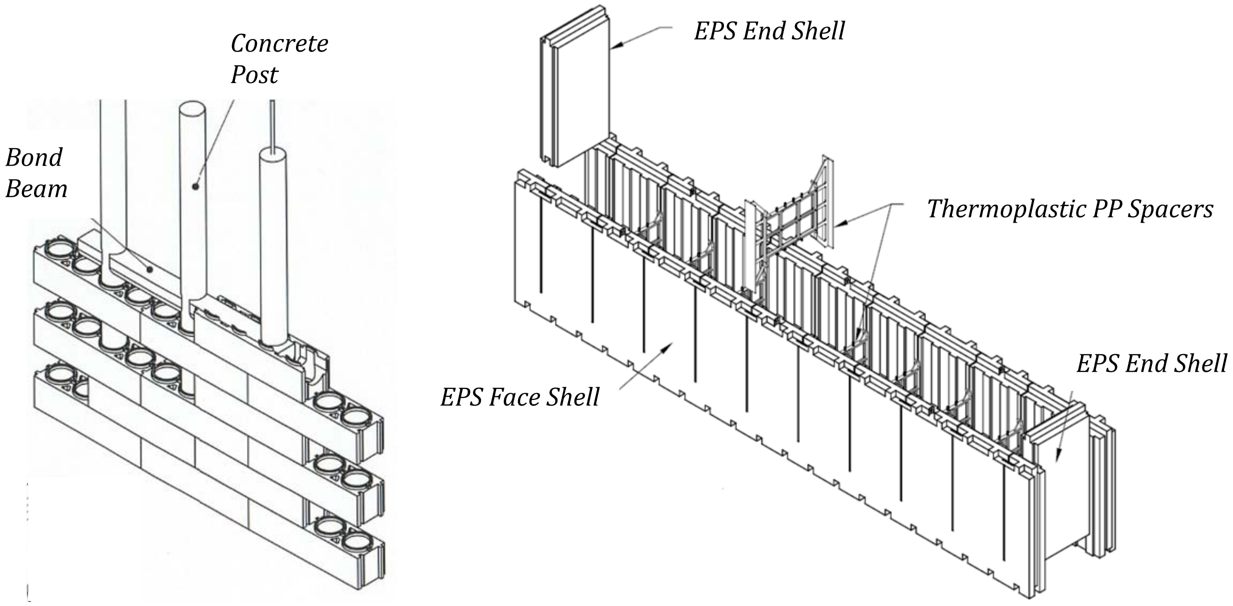
One of the major advantages of masonry noise barriers is their durability under various weathering effects including freeze-thaw cycles and prolonged exposure to sunlight and moisture. The Canadian standard CSA Z107-9-00 [21] and HITEC [8] require a minimum maintenance-free lifespan of 20 years for noise barriers. Masonry noise barrier systems have often demonstrated much longer life spans than the required 20 years. In terms of weathering resistance, clay masonry units are classified as severe weather (SW), moderate weather (MW) and normal weather (NW) in ASTM C62 [12], based on their maximum water absorption after 5 h submersion in boiling water and maximum saturation coefficient, the ratio of water absorption after 24 h submersion in cold water to that after 5 h submersion in boiling water. The scaling resistance of concrete masonry noise barriers against deicing chemicals is determined according to ASTM C672 [31]. HITEC [8] also requires noise barriers to be resistant to the growth of microorganisms and fading caused by long term solar exposure, both of which are satisfied by masonry noise barriers.

RECENT DEVELOPMENTS

Different proprietary masonry noise barrier systems have recently been developed using mortarless lightweight polymeric hollow masonry units to enhance noise reduction and reduce construction cost and time. One such system is made of hollow, interlocking, polyurethane masonry units in which, depending on the design requirements, some of the cores of these units are reinforced with steel and then filled with concrete [32] as shown in Figure 2-a. This system is faster and easier to construct than conventional noise barrier systems and has enhanced noise attenuation properties, a STC value of 50 [32]. Another example of recent masonry noise barrier systems is the light weight polystyrene unit system shown in Figure 2-b that consists of hollow expanded polystyrene (EPS) modules which snap together on site by tongue and groove connection to form a hollow box, which is then reinforced and filled with concrete [33].

The structural design of such modern masonry noise barrier systems is not yet covered in the current design codes. Therefore, HITEC [8] requires that the load-deflection behavior of the noise barrier wall panel under transverse loading be tested in accordance with ASTM E72 [34], where cyclic transverse loading is applied to the specimen up to failure. The elastic limit and bending strength are determined from this test. Tests should be conducted once under uniform load, to study the effect of wind and seismic loading, and another under concentrated transverse load on short specimens to study the shear behavior of the panel.

New noise barrier systems need to be designed to minimize collection of water, dirt and debris within its components [8]. Long term creep and shrinkage of polymeric materials should be taken into account in the design stage [1]. These materials are also prone to color degradation under prolonged exposure to sunlight UV radiation, for which stabilizers and absorbers are added to the material chemical composition to protect it from UV radiation [1]. HITEC [8] requires coating to be applied to all surfaces of the noise barrier to protect them from atmospheric corrosion, UV radiation and exposure to road salts.



a) Polyurethane Units [32]

b) Expanded Polystyrene Units [33]

Figure 2: Mortarless Interlocking Polymeric Masonry Noise Barrier Systems

SUMMARY AND CONCLUSION

The most common masonry noise barrier systems were discussed and the provisions of the current design codes and guidelines were reviewed including acoustic performance, durability, and architectural considerations. Masonry noise barrier systems are suitable for construction in almost all regions and lend themselves to both on-site and off-site construction. Hollow masonry noise barriers are light enough to reduce mass induced seismic forces, and heavy enough to have high sound transmission loss. They are also aesthetically preferable relative to other materials. Masonry noise barriers have exhibited long term durability under inclement weather conditions. Masonry Noise barriers constructed according to the provisions of CSA or ASTM standards satisfy the required resistance to freeze-thaw cycles and exposure to moisture over the specified life span of the noise barrier. Masonry noise barriers can also withstand long term solar exposure without color degradation.

The structural design of masonry noise barrier systems made of concrete or clay masonry units is performed in accordance with the applicable local masonry design codes. As specified in the current design codes, transverse wind and seismic forces are the governing loads for noise barriers. Existing codes also pose geometric restrictions on noise barriers to satisfy the required minimum level of noise reduction without disrupting the aesthetics of the surroundings.

Current design codes do not accommodate the structural design of recently developed masonry noise barriers made of lightweight polymeric units to improve constructability and acoustic efficiency. Therefore, the resistance of these noise barrier panels to transverse loads is determined experimentally, which is not a cost effective approach to design. This calls for research on the structural behavior and design of noise barrier systems constructed using innovative masonry units.

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