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Nota Técnica:
Proyecto y ejecución de un arco pretensado con residuos plásticos de origen doméstico

Technical Note:
Design and construction of prestressed arch using plastic shoppers waste

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RESUMEN

Desde su desarrollo durante el siglo pasado y debido a su versatilidad, el plástico se ha hecho ubicuo en la sociedad actual. Los problemas surgen cuando este material, sobre todo cuando conforma bienes de consumo, se desecha. Actualmente, los índices de valorización y reciclado de residuos plásticos de origen doméstico son muy bajos. El sector de la construcción tiene una enorme potencial para reutilizar este tipo de residuos, que se pueden comprimir para fabricar bloques. Este artículo presenta un uso innovador de los bloques de residuos plásticos: la construcción de un arco estructural pretesado. Describe el proyecto y la ejecución de un arco estructural construido con estos materiales de desecho.

Palabras clave: bloques comprimidos de residuos plásticos, arco estructural, valorización, material de construcción, viscoelasticidad.

SUMMARY

Since the development of plastic in the last century, being versitile it has become very popular for diversified uses. The problem appears when these plastics, particularly shoppers are disposed as waste. The current reuse and recycling rates for the plastic shoppers waste are very low. Construction Industry has a great potential for the reuse of shoppers waste. Shoppers waste has been compressed to fabricate compressed shoppers waste (CSW) blocks. This study is related to an innovative reuse of CSW-blocks for the construction of prestressed structural arch. This paper is dedicated to the design and construction of structural arch using shoppers waste as a material.

Keywords: *compressed shoppers waste (CSW) block, structural arch, reuse, construction material, visco-elastic.*

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1. INTRODUCTION

Plastic shopper bags have become a major environmental concern in many countries around the world. Scientists and engineers are trying to find out environment friendly solutions to dispose them off. Reuse of waste is one of the best alternatives to control waste problems. Till now reuse/recycle industry for shoppers waste is almost none. Construction industry has a great potential to reuse huge quantities of the waste. Compressed shoppers waste (CSW) blocks have been fabricated for use as a construction material. The engineering properties of CSW-blocks required for design have already been investigated and published (1). The elastic properties are important for short term loading and used for design of prestressing cables. Other properties, termed as elastic strain index (ESI) and viscous strain index (VSI) are required to predict the post construction deformations/deflections. Design charts relating VSI and ESI with block density and applied stress have been developed and published (1).

Other materials used in the arch include, prestressing cable, shaping struts, tension stirrups, wooden wedges, cable clamps and the end plates. The arch construction requires no adhesive for bonding of the CSW-blocks. During construction the blocks are held together by the pre-stressing cables and when the arch is erected and subjected to service loadings, the blocks are held in position by the arching action.

A detailed design exercise for a test arch has been carried out. Procedural steps for the construction of arch are briefly discussed. The load testing of the arch to check the design and post construction performance has been published (1). The uses and limitations of the arch are also discussed. The application of research will bring revolution in the fields of civil and environmental engineering.

2. LITERATURE SURVEY

High density polyethylene (HDPE), low density polyethylene (LDPE) and linear low-density polyethylene (LLDPE) are commonly used for manufacturing plastic shopper bags. The amount of plastic waste produced from bags, sacks and wraps only, excluding other packaging and trash bags entering the U. S. municipal solid waste stream (MSW) in 2003 was estimated at 19.49 million tons and an overall recycling rate was 2.4 percent (2). The demand for HDPE will grow to 31.3 million tons in 2009 (3). The publication Northumberland Today says 25 millions plastic shopper bags are produced every day in Canada (4).

Among the numerous hazards due to shoppers waste, some of the very serious are floods, deterioration of landscape, delaying decomposition of solid waste, threat to marine wildlife, toxic gas emission through burning and landslides (4, 5). Shopper bags waste has become a challenging problem for the environmentalists. Multiple solutions to get rid of the waste are under consideration for the last decade but proved ineffective to fully control the waste problems (4). The best workable solution to tackle any waste is the reuse or recycling. An attempt for reuse of shoppers waste in low weight embankment for pavements construction on soft soils has already been made (6).

The behavior of the arch using CSW-blocks is similar to the masonry arches. Masonry arches derive their load-carrying capacity from their curved geometry, which causes only compressive forces to develop between adjacent blocks. The primary loading on masonry arches is normally their self-weight. Unusual loadings, such as high concentrated point loads, can cause severe bending and possible failure to occur since the funicular line for the loading cannot be contained easily within the dimensions of the arch. Such loadings are to be avoided unless the arch is specially shaped to receive them. In most cases, however, dead loads far exceed live loads and the compressive forces associated with the dead weight of a masonry arch typically dominate the possible tension forces that could result from live-load variations, with the consequence that such arches can usually withstand a reasonably diverse group of loading patterns without collapsing (7).

The most common relationship between the radius 'R' of a circular arch, the horizontal span 'L' and central rise 'y_c' is as follows (8).(Eq [1])

$$R = \frac{L^2}{8y_c} + \frac{y_c}{2} \qquad [1]$$

3. MATERIAL PROPERTIES AND DESIGN CHARTS

The relevant design charts are shown in Figs. 1, 2 and 3.

The required design properties include the yield strength and modulus of elasticity of the cables and stirrups. The modulus of elasticity and yield strength of the stirrups used are 970 000 kpa and 730 000 kpa respectively and the values for the cable are 4 035 000 kpa and 240 000 kpa respectively. Poisson's ratio for the blocks = 0.17.

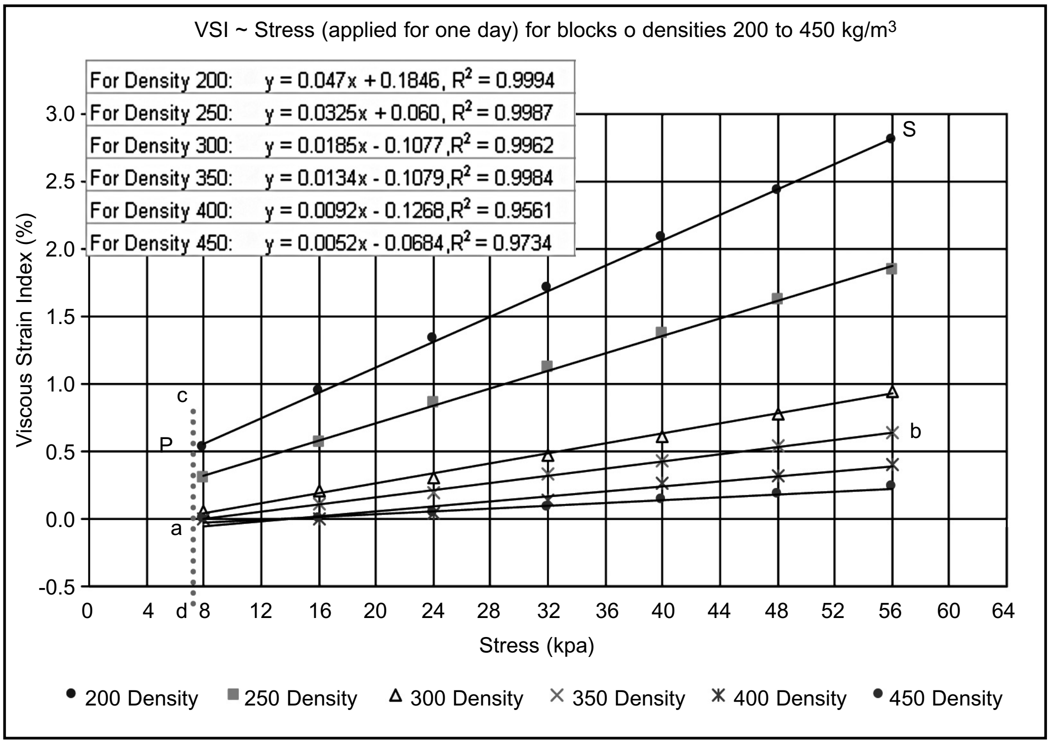

Figure 1. VSI ~ Stress (Design Chart-1).

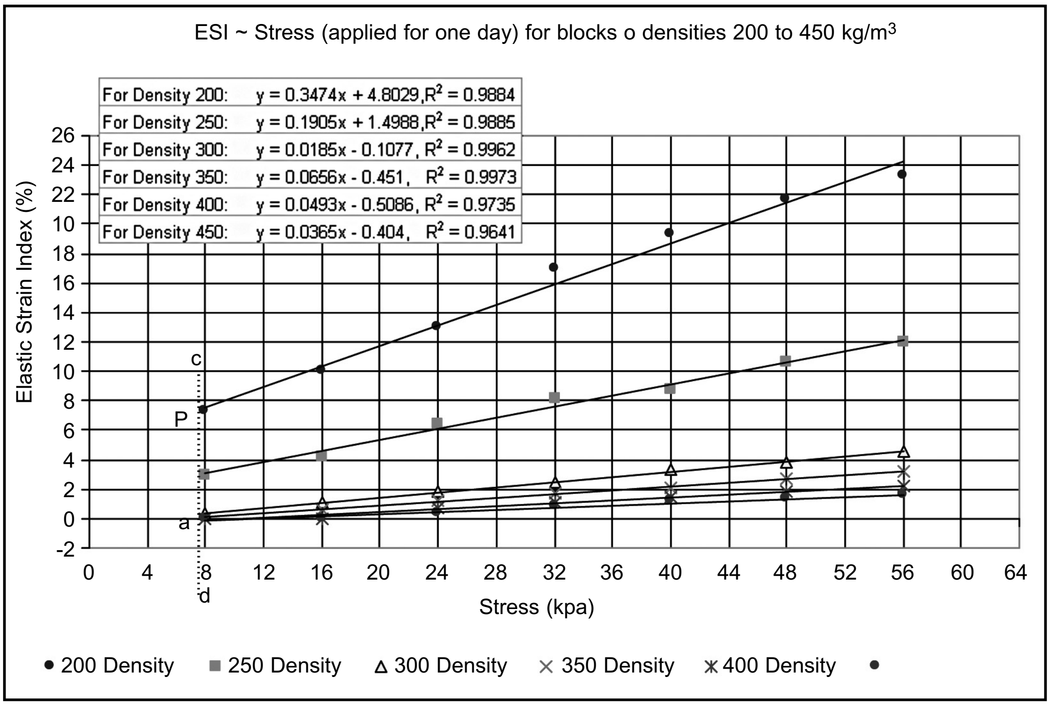

Figure 2. ESI ~ Stress (Design Chart-2).

4. DESIGN OF ARCH

Considering the design of an arch for an industrial or parking shed subjected only to the self loading.

4.1. Design Data

Arch Type = Circular Arch
Span of Arch = L =3630 mm
Crown height = y_c =880 mm

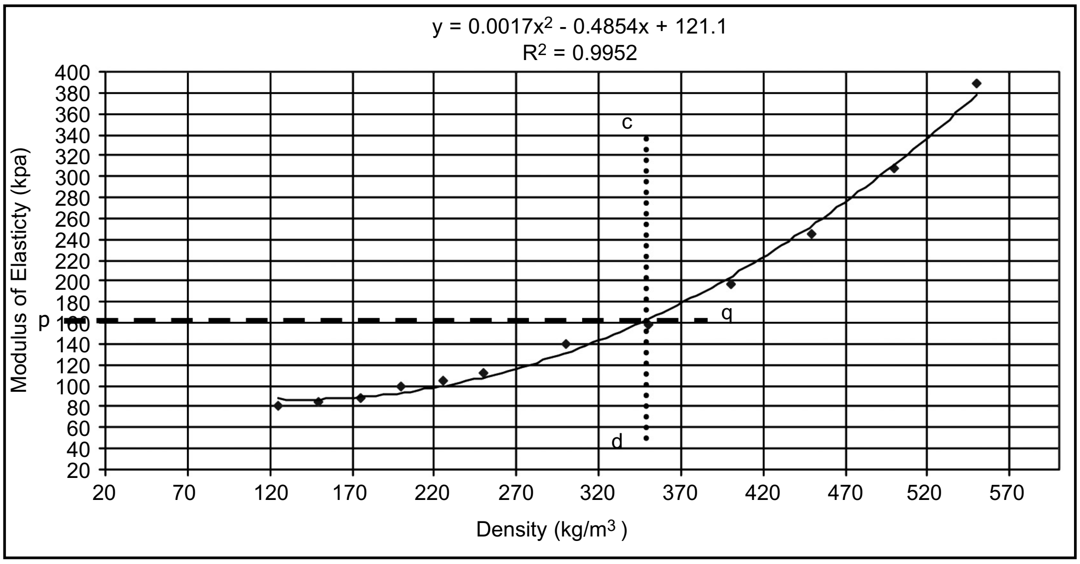

Figure 3. Modulus of elasticity ~ block density. (Design Chart-3).

Applied loads = Self load
Permissible deflection = Δ_p = zero for self loading
Design life = 50 years

From the given data determine the remaining basic data, as follows;

Radius of arch [2] =

$$R_B = \frac{L^2}{8y_c} + \frac{y_c}{2} = 2311.7\,\text{mm} \qquad [2]$$

Angle subtended by the arch at the center [3] =

$$\theta = 2\sin^{-1}\left(\frac{L}{2R}\right) = 1.8rad \qquad [3]$$

Length of arch along the bottom chord =

$$S_B = R\theta = 4174.54mm$$

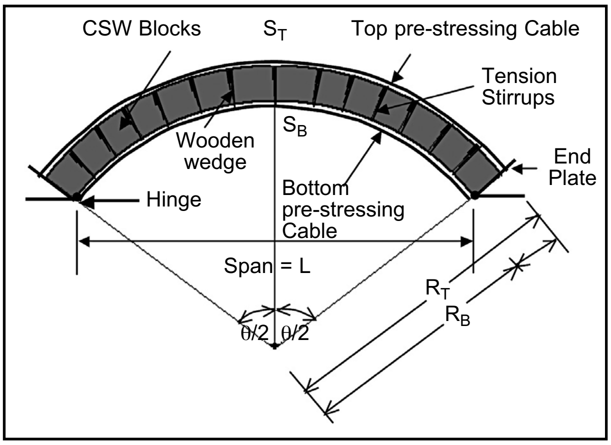

Figure 4. Model of a circular arch.

4.2. Selection of a Trial CSW-Block

Considering an arch model shown in Fig: 4, relevant properties for a trial CSW-block are the density and the height, both before and after pre-stressing. Width and length of block do not affect the design process but defines only the cross section of an arch. Height and density, however, are the important parameters which greatly affect the design.

4.2.1. Properties of the Trial Block before pre-stressing

Let the initial properties of the trial block be as follows;

Density before pre-stressing = g_I = 200 kg/m^3
Weight of block = 23.0 kg = 0.23 kN (same weight before and after pre-stressing)
Height of block before pre-stressing = H_I = 425 mm
Width of block before pre-stressing = B_I = 417.5 mm
Length of block before pre-stressing = L_I = 650 mm

4.2.2. Properties of the Trial Block after Pre-stressing

Pre-stressing changes the block height and hence the density, width and length will also slightly change due to lateral expansion.

Let the properties of trial block after pre-stressing are as follows;

Density of block after pre-stressing = g_P = 350 kg/m^3
Height of block after pre-stressing = H_P = 250 mm

In the arch, width of block becomes depth 'D' of arch as shown in Fig: 4. Length of the block becomes width of arch and height of block multiplied by the number of blocks determines the length of the arch rib.

Therefore,

Number of blocks in the arch [4] =

$$N = \frac{S_B}{H_P} = \frac{4174.54}{250} = 16.69 \approx 17 \qquad [4]$$

Adjust the height (final height = H_{PF}) to get "N" a whole number

Finally the number of blocks in the Arch [5] =

$$N_F = \frac{S_B}{H_{PF}} = \frac{4174.54}{245.55} = 17 \qquad [5]$$

Where,

H_{PF} is the final height of block after pre-stressing = 245.55 mm

Self weight of arch [6] = N_F x W_B =17 x 0.23 = 3.91 kN [6]

UDL on arch [7] =

$$\frac{\textit{Self}\text{ weight of arch}}{\textit{Length}\text{ of Arch}} = \frac{3.91}{3.63} = 1.08\, kN/m \qquad [7]$$

From usual structural analysis determine the axial force "F_A" induced in the arch rib due to self loading. Axial force is maximum at the supports and minimum at the crown of the arch. From the structural analysis, average axial force, F_A = 2.38 kN.

4.3. Design of Pre-stressing Cable

The pre-stressing was made by mechanical jacks and the time for pre-stressing to fabricate the arch ranged from 20 to 30 minutes, therefore the design Chart-3 (Ref. Fig: 3) has been directly used for cable design. From the design chart-3, determine "E" against density.

For γ_P = 350 kg/m^3, the value of E from the design Chart 3 is, E = 160 kpa
Reduction of CSW-block height after pre-stressing [8]

$$H_R = H_I - H_{PF} = 425 - 245.55 = 179.45 \text{ mm} \qquad [8]$$

Pre-stressing strain [9] =

$$\varepsilon_P = \frac{H_R}{H_I} = \frac{179.45}{425} = 0.422 = 42.2\% \qquad [9]$$

Pre-stressing stress = σ_P = E x ε_P = 160 x 0.422 = 67.5 kpa
Load Factor = 1.5 (However it is a short time stress and rapidly reduces due to stress relaxation, and under service condition the cable becomes dormant)
Design stress = 1.5 x σ_P = 1.5 x 67.5 = 101.25 kpa
Initial cross-sectional area of the arch = 417.5 x 650 = 271375 mm^2 = 2714 cm^2
Poisson's ratio of CSW-blocks = 0.17

Pre-stressing strain [10] =

$$\varepsilon_P = \frac{H_R}{H_I} = \frac{179.45}{425} = 0.422 = 42.2\% \qquad [10]$$

Lateral strain = 0.17 x 42.2 = 7.174 %
Increase in length = 0.07174 x 650 = 46.63 mm
Length of block after pre-stressing L_P = 650 + 46.63 = 696.63 mm
Width of block after pre-stressing = B_P = 417.5 + 0.07174 x 417.5 = 447.45 mm
Final cross-sectional area of arch after pre-stressing = A_F = 696.63 x 447.45 = 3117.0 cm^2
Force induced in the arch rib due to pre-stressing = F = 101.25 x 0.3117 = 31.56 kN.
No. of cables = 4

Tensile force per cable = [11] =

$$T = \frac{F}{4} = \frac{31.56}{4} = 7.89\,\text{kN}. \qquad [11]$$

Yield stress of cable = F_{YC} = 240000 kN/m^2

Required area of cable [12] =

$$A_C = \frac{T}{F_{YC}} = \frac{7.89x10000}{240000} = 0.328\,\text{cm}^2 \qquad [12]$$

Diameter of cable [13] =

$$D_C = \sqrt{\frac{A_C \times 4}{\pi}} = 0.646\,\text{cm} \approx 6.5\,\text{mm} \qquad [13]$$

4.4. Design of Tension Stirrups

Tensile force induced in the cable due to pre-stressing = T = 7.89 kN
Force induced in the stirrup = Radial component of 'T' = F_S = 2T sin β
F_S = 2 x 7.89 sin 0.10588 = 1.66 kN. (Ref. Fig: 5)
Where, β is the angle subtended by one block [14]

$$\beta = \frac{\theta}{N_F} = \frac{1.8}{17} = 0.10588\,\text{rad}. \qquad [14]$$

Stirrup has two legs.

Force in one leg [15] =

$$\frac{F_S}{2} = \frac{1.66}{2} = 0.83\,\text{kN}. \qquad [15]$$

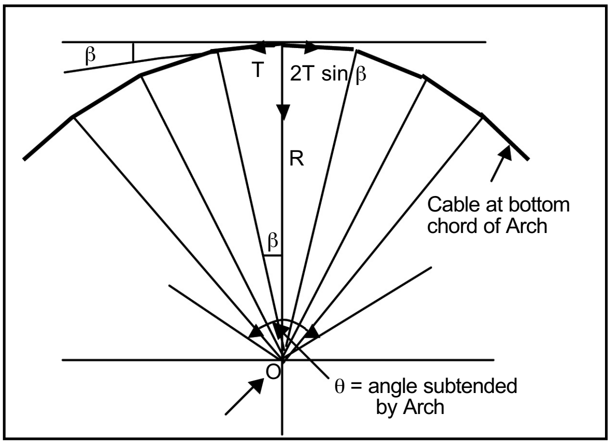

Figure 5. Shows center 'O' of Arch, angle 'θ' subtended by the Arch, Cable at bottom chord, angle ',' subtended by one block and tension 'T' in the cable.

Load factor has already been applied for cable tension therefore the above force is also the design force.
Yield stress of Stirrup = F_{YS} = 730000 kpa

Required area of stirrup [16] =

$$A_S = \frac{F_S}{F_{YS}} = \frac{0.83x10000}{730000} = .0113cm^2 \qquad [16]$$

Diameter of stirrup [17] =

$$D_S = \sqrt{\frac{4}{\pi}(A_S)} = 0.12cm = 1.2mm \qquad [17]$$

Length of stirrup ring = Width of block = B_P =417.5 mm

4.5. Design of Shaping Struts

To get the required shape (curvature) of the arch, shaping struts are required to be provided between the blocks for uniform compression of all the blocks.

Length of arch along the bottom chord = S_B =4174.54 mm
Radius of the top chord = R_T = R_B + B_P = 2311.7 + 417.5 = 2729.2 mm (D = B_P, Ref. Fig: 4)
Length of arch along the top chord = S_T = R_T x ı = 2729.2 x 1.8 = 4912.56 mm

Length of the strut along the top chord [18] =

$$L_{ST} = \frac{S_T}{N_F} = \frac{4912.56}{17} = 288.97\,\text{mm} \qquad [18]$$

Length of the strut along bottom chord [19] =

$$L_{SB} = \frac{S_B}{N_F} = \frac{4174.54}{17} = 245.56\,mm \qquad [19]$$

Pre-stressing cable passes through the strut. Diameter of the strut should be slightly greater than the cable diameter. Any lightest available mild steel tube section is enough to be used as a strut. However recommended minimum values are as follows;

Outer diameter of strut (steel tube) = 20 mm
Wall thickness = 1.5 mm

Shaping struts are used to provide required curvature to the Arch. During pre-stressing successive compression of the blocks occurs. The blocks closest to the end plate where pre-stressing force is applied are compressed first and will compress more than the required value if shaping struts are not provided. With the shaping struts in position, the blocks will only compress to the required value and will transfer the stress to the next block. If there exists some friction between the cable and tension stirrup, the transfer of stress to the next block will be restricted resulting in additional stress on the shaping strut causing its crushing or buckling. But there are no chances of such friction and failure of shaping strut. However determination of such friction and quantitative design of struts is beyond the scope of this paper.

4.6. Design of Wooden Wedge

Due to curved shape of the arch, the length of top chord is greater than the bottom chord. If wooden wedges are not provided between the blocks, the blocks will compress to a trapezoidal shape. The density and hence the strength of the blocks along the depth of the arch will not be uniform. This will result in excessive deflection of the arch. Therefore for uniform compression of the block to attain parallelepiped shape, wedges are to be provided between all the blocks. For usual lightly loaded arches (mainly the dead load), any low to medium quality wooden wedge will be strong enough to resist the compressive stresses due to service loads.

Shape of the wedge = Isosceles triangular wedge (Ref. Figure 9)
Base width of the wedge = L_{ST} - L_{SB} = 288.97-245.56 = 43.41 mm
Height of the wedge = Depth of the arch = D = B_P = 417.5 mm

4.7. Design of End Plate

End plates are used for pre-stressing of the blocks during fabrication of the arch. When the arch is erected on its supports, the plates become dormant. Any low quality wooden planks can be used to make the plates.

Length of plate = Length of block = L_P = 650 mm
Width of plate = Width of block = B_P = 417.5 x 420 mm
Thickness of plate = minimum 50 mm
Four holes with diameter slightly larger than the diameter of the cable.
Distance from edges of the plate for the holes = at least 100 mm along length and 50 mm along width.

5. CHECK FOR DESIGN (PERMISSIBLE DEFLECTION)

Deflection of the arch actually occurs due to shortening of the arch rib resulting from compression of the CSW-blocks due to stresses induced by loading. It is laborious to calculate the deflection directly since the geometric properties of the arch changes with deflection as shown in Fig. 6. Therefore the check for permissible deflection is made indirectly as follows.

The permissible reduced Arch length due to Permissible deflection is calculated and compared with the actual reduced length due to compression of blocks resulting from applied stress.

Permissible deflection = Δ_p
Permissible crown height = $y_c - \Delta_p$

From equation [1], calculate the final radius "R_F" of the arch using permissible crown height and the span.

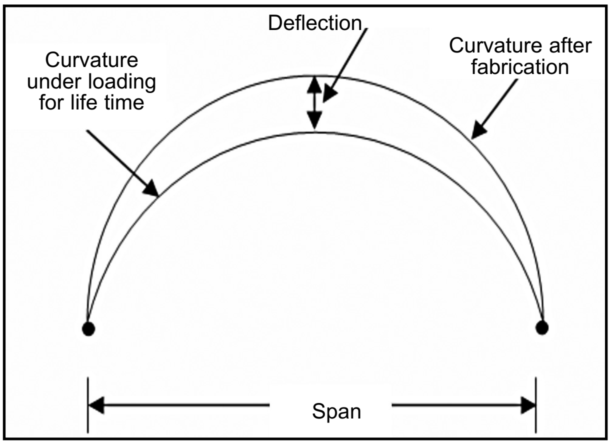

Figure 6. Change of curvature due to deflection.

Angle subtended by the deflected arch due to permissible deflection [20] =

$$\theta = 2Sin^{-1}\left[\frac{L}{2R_F}\right] \quad [20]$$

Permissible reduced length of arch due to Permissible deflection = $S_{BP} = R_F \times \theta$
If S_{BR} x S_{BP}, design is OK. Otherwise revise the design steps with a block of higher density. Where, S_{BR} is the actual reduced arch length due to compression of blocks. Load testing and calculation of S_{BR} and crown deflection has already been published (1).

6. CONSTRUCTION OF ARCH

A model CSW-blocks arch shed is shown in Fig. 7. Methodology for the construction/fabrication of CSW-blocks arch is quite unique. The step wise procedure for fabrication is discussed as follows:

6.1. Materials

The component parts of the arch include the following;

6.1.1. Compressed plastic shoppers waste (CSW)-blocks

The CSW-blocks comprise the main material for the arch. The blocks of required density before pre-stressing are selected in the design according to section 4.2.1. Depending on the geometrical properties, the number of blocks is decided according to section 4.2.2.

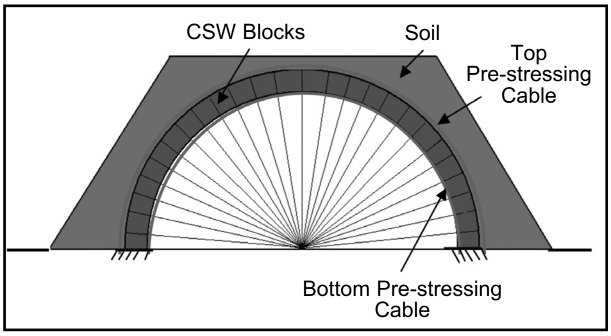

Figure 7. CSW-blocks arch shed.

6.1.2. Pre-stressing Cable

Four cables are required to fabricate for one arch. The length of the cable depends on the number, height of the block and extra length on each end to be attached to the pre-stressing jacks. The working stresses can only be applied in the direction as that of the application of pressure during fabrication of blocks to avoid buckling. Therefore the block will be laid such that the height of the block is along the axis of the arch. Accordingly the length of each cable will be equal to the number of blocks multiplied by the height of the block plus 4-ft. (2-ft. extra required to attach the cable with the jack on either side). The extra length will however vary depending on the type of pre-stressing jack. The diameter of the cable has been designed as described in section 4.3.

6.1.3. Wooden Wedges

As discussed in section 4.6 wooden wedges are required for uniform compression of the blocks along top and bottom chords of the arch. The size is designed according to section 4.6. The number of required wooden wedges is equal to the number of blocks minus one.

6.1.4. Stirrups

The stirrups are required to hold the cables in position. They are subjected to tensile forces. The diameter of the stirrup has been designed as in section 4.4. The shape is shown in Figs: 8 and 9. The length of the stirrup is equal to the width of block.

6.1.5. Shaping Struts

The shaping struts are required for uniform compression of all the blocks. They are provided to get the required shape (curvature) of the arch. Parabolic arches are also possible if struts of designed lengths are provided at designed locations. The design of the struts has already been discussed in section 4.5. The number of struts both along the top and bottom chords is equal to the number of blocks multiplied by two.

6.1.6. End Plates

End plates are used for pre-stressing of the blocks during fabrication of the arch. When the arch is erected on its supports, the plates become inactive. Two plates are required for one arch. Each plate has four holes for the cables. The design has been discussed in section 4.7.

6.1.7. Cable Clamps

Clamps are required for the cable to retain/lock up the applied pre-stressing force. Eight clamps are required for one arch. Ordinary clamps as per size of the cable are sufficient to retain the designed pre-stressing force.

6.2. Equipment

The equipments required for the fabrication of pre-stressed arch are very simple and comprise of pre-stressing jacks and spanners. The jacks should be strong enough to apply the design pre-stressing force. Eight jacks are required, two at each end of four cables for efficient fabrication of the arch. Even two jacks can be used for fabrication but it will simply increase the fabrication process by four times. Spanners of suitable size to tight the clamp bolts are also required for fabrication of the arch.

6.3. Arrangement of the components

Four cables are passed through the holes of the end plates. Leaving 2-ft. extra length of the cable beyond the end plate (for fitting with the jacks) clamps are fastened. Two longer shaping struts and shorter struts are passed through the lower cables and upper cables respectively. Then a block is placed as shown Fig: 8. The dimensions of the block shown are the same as during the block fabrication. Next to the block, wooden wedge and stirrups are placed as shown in Fig: 8. similarly all the blocks and others parts are arranged and laid in a straight line as shown in Fig: 9. The cables are stretched manually as tight as possible and the clamps locked at both the ends. In this position the top chord is touching the floor.

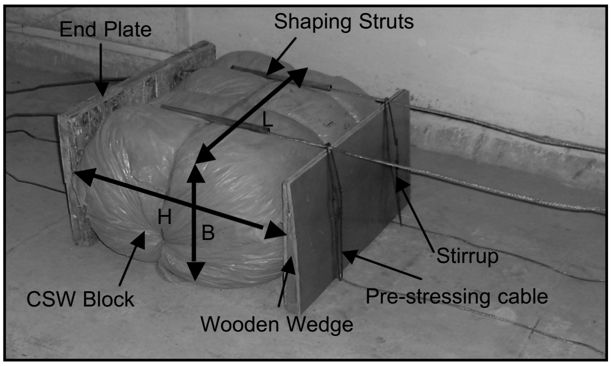

Figure 8. Sequence of laying the arch.

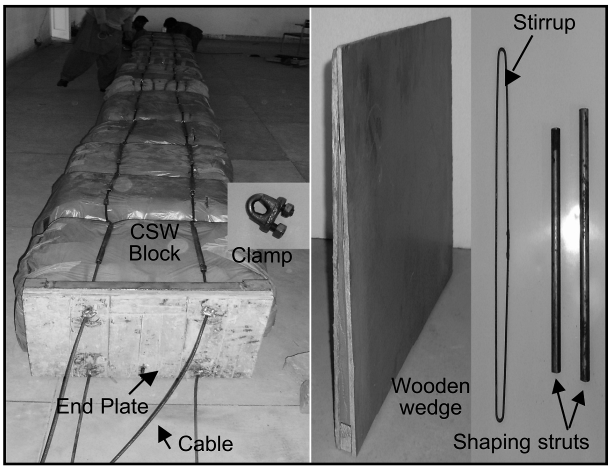

Figure 9. CSW-blocks laid in straight line, cables, shaping struts, stirrups, clamp and end plate.

6.4. Pre-Stressing

After application of sufficient pre-stressing force to tightly hold the blocks, the entire arch is turned by 90º to lie on its side. Further pre-stressing force is then applied to compress the blocks and arch starts achieving the curvature as shown in Figs: 10 and 11. The arch curvature depends on the length of the shaping struts along the top and bottom chords. Since the width of the wooden wedges is equal to the difference in lengths of the struts, the arch attains the required curvature yet the compression of the blocks along its width is uniform.


Figure 10. The arch gradually curving by pre-stressing.


Figure 11. Pre-stressing for fabrication of Arch.

Arch lying on its side is shown in Fig: 11. One mechanical pre-stressing jack seen on left. The end blocks are fully compressed to the required level and shaping struts are touching each other. While the inner blocks are yet to be compressed, the gap between the shaping struts and the wooden wedges are visible.

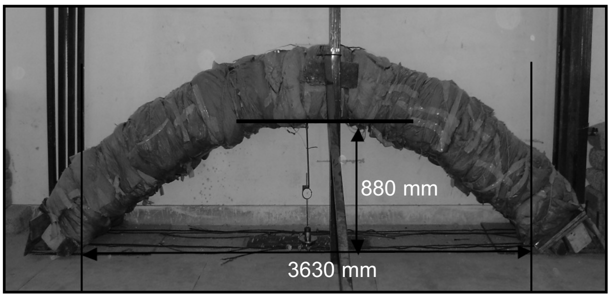

Figure 12. CSW-blocks Arch in upright position.

When the pre-stressing is completed and all the struts are touching one-another and the arch has achieved the designed curvature, the arch is turned to the upright position as shown in Fig: 12.

7. LOAD TESTING OF ARCH

A pre-stressed arch designed above was fabricated for test loading. Two test loads i.e., self load, and loaded with 116-cement mortar blocks (UDL = 479.33 kg/m) were applied and crown deflection was measured at different time intervals. An arch subjected to test loading is shown in Fig: 13. An arch subjected to unsymmetrical loading is also shown in Fig: 14. Comparison of observed and calculated deflections has already been published (1).

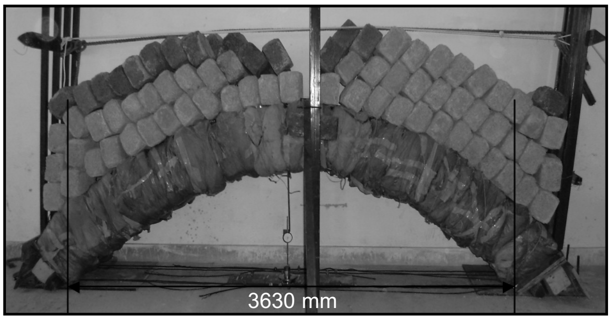

Figure 13. CSW-blocks Arch subjected to self + imposed loading.

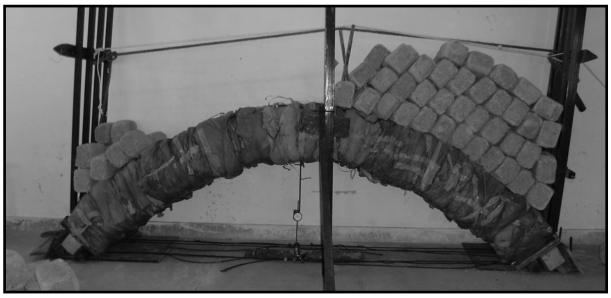
Figure 14 Arch subjected to unsymmetrical loading.

8. USES AND LIMITATIONS

- Due to excellent insulation properties it is most suitable for cold and other storage sheds.
- Will be suitable for active earthquake zones, since the arch will withstand shocks through twisting without structural damage by virtue of its flexiblity and ability to resist short term unsymmetrcal loading.
- Structurally the arch may be termed as flexible multiple hinge arch and individual arch will be subjected to lateral buckling. Therefore for any building shed, series of closely placed CSW-blocks arches will be required to be contained within spandral concrete arches.
- The main aim is to control the shoppers related pollution problems but can be used as an alternate material. The material is cost effective as compared to convential concrete arches (9) and the benefits in terms of controlling environmental problems are countless.

- The CSW-blocks as a construction material are mainly recommended for subsurface applications due to long life under fairly uniform temperature conditions and no fire risks.
- Parabolic arches can be fabricated using shaping struts of proper size placed at proper locations. However the most stable are the circular arches.

9. CONCLUSIONS

- Design procedure is quite simple and similar to the conventional methods and final design may require fewer iterations by an experienced designer.
- The use of design charts is conservative for the design and construction of arches in areas where life time service temperatures are below that of the temperatures at which tests for development of the deign charts are made.
- Design and construction of arches subjected to dead loads or uniformly distributed symmetrical loads can be made with confidence.
- The fabrication procedure of the arch is quite simple.
- The arch can safely withstand short term unsymmetrical loads that may be applied during erection of arch or during earthquake shaking.
- Structurally, the arch can be termed as multiple hinge flexible arch therefore the design is applicable for the construction of arches subjected only to the symmetrical loads.

LIST OF SYMBOL

ESI = Elastic Strain Index
VSI = Viscous Strain Index
Y_C = Crown height of arch
L = Span of arch
D = Depth of arch
θ = Angle subtended by the arch
R_B = Radius of bottom chord
R_T = Radius of Top chord
S_T = Length of arch along top chord
S_B = Length of arch along bottom chord
γ_P = Density of block after pre-stressing
γ_I = Density of block before pre-stressing
W_B = Weight of block
H_{PF} = Final height of block after pre-stressing
N_F = Final number of blocks in arch
B_P = width of block after pre-stressing
L_P = Length of block after pre-stressing
H_P = Height of block after pre-stressing
B_I = Width of block before pre-stressing
L_I = Length of block before pre-stressing
H_I = Height of block before pre-stressing
H_R = Reduction in block height after pre-stressing
F_A = Axial Force in the arch
A_F = Final cross-sectional area of arch after Pre-stressing
F = Induced force in the arch rib
σ_A = Axial thrust in the arch
σ_D = Design axial thrust in the arch
E = Modulus of Elasticity
ε_P = Pre-stressing strain
σ_P = Pre-stressing stress in cable
F_{YC} = Yield stress of Pre-stressing cable
A_C = Area of Pre-stressing cable
D_C = diameter of Pre-stressing cable
F_S = Force induced in tension stirrups
T = Tension force in Pre-stressing cable
F_{YS} = yield stress of tension stirrups
A_S = area of tension stirrups
D_S = diameter of tension stirrups
L_{ST} = Length of shaping strut along top chord
L_{SB} = Length of shaping strut along bottom chord
R_F = Final arch radius after deflection
S_{BP} = Permissible reduced length of bottom chord of arch due to permissible deflection.
S_{BA} = Actual permissible reduced length of bottom chord of arch due to compression of blocks

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