# EXPERIMENTAL EVALUATION OF HYBRID BARRIER SYSTEM FILLED WITH WASTE MATERIALS

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I certify that in my opinion the thesis submitted by Zagros Othman ALI titled "EXPERIMENTAL EVALUATION OF HYBRID BARRIER SYSTEM FILLED WITH WASTE MATERIALS " is fully adequate in scope and in quality as a thesis for the degree of Master of Civil Engineering.

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Zagros Othman ALI

## ABSTRACT

**M. Sc. Thesis**

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**Institute of Graduate Programs**
**The Department of Civil Engineering**

**Thesis Advisor:**
**Assist. Prof. Dr. Halil İbrahim YUMRUTAŞ**
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Barrier systems are one of the main factors to diminish fatal traffic accidents. Research in the literature focused on developing concrete, steel and only few timber barriers but the aesthetic and environmental effects of such barriers were neglected or not discussed extensively. Waste material management has been a big deal of the world with the technological and industrial development. This study presents a novel approach to hybrid barriers produced with timber, and waste materials (slag and tire). Therefore, the aim of the study is to contribute to highway safety aesthetically, economically, and environmentally. In this regard, pendulum experiments were conducted to observe the performance of the proposed hybrid barrier type considering EN 1317 standard. Hybrid barriers filled with sand and slag had similar results with A-class ASI index and W6 class working width and successfully passed the limits however the hybrid barrier filled with tire did not be able to meet the requirements. The hybrid barriers can be offered as an aesthetic and pleasant alternative to conventional barrier types, especially in scenic, mountainous, rural and historical places. This study is thought to contribute reducing environmental pollution by using recyclable materials and to diminish the cost of conventional timber barriers. Additionally, the outcomes of this study will encourage the utilization of various waste materials in future studies.

**Key Words** **:** Hybrid barrier, wooden barrier, Crashworthiness, Guardrail, Pendulum, Waste Material, Slag, Tyre.

**Science Code** **:** 91124

## ÖZET

**Yüksek Lisans Tezi**

**ATIK MALZEMELER İLE DOLDURULAN HİBRİT BARİYER SİSTEMİNİN DENEYSEL OLARAK İRDELENMESİ**


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Bariyer sistemleri ölümcül trafik kazalarının azaltılmasında ana faktörlerden biridir. Literatürdeki çalışmalar beton, çelik ve çok azı ahşap bariyerlerin geliştirilmesine odaklanmış ancak bu bariyerlerin estetik ve çevresel etkileri ihmal edilmiş veya yeterince tartışılmamıştır. Teknolojik ve endüstriyel gelişmelere bağlı olarak atık malzeme yönetimi Dünyada önemli bir sorun haline gelmiştir. Bu çalışma ahşap ve atık malzemeler (cüruf ve lastik) ile üretilen hibrit bariyerlere yeni bir yaklaşım ortaya koymuştur. Çalışmanın amacı karayolu güvenliğine estetik, ekonomik ve çevresel anlamda bir katkı sağlamaktır. Bu bağlamda önerilen hibrit bariyerin performansının gözlemlenebilmesi için EN 1317 standardı doğrultusunda pandül testleri gerçekleştirilmiştir. Kum ve cürüf ile doldurulan hibrit bariyerler A sınıfı ASI indeksi ve W6 çalışma genişliği sınıfı ile benzer sonuçlar ortaya koymuş ve limitleri sağlamıştır ancak atık lastik ile doldurulan hibrit bariyer gerekli şartları sağlayamamıştır. Hibrit bariyerler özellikle manzaralı, dağlık, kırsal ve turistik yollarda konvansiyonel bariyerlere estetik ve hoş bir alternatif olarak önerilebilir. Bu çalışma ile geri dönüştürülebilir malzeme kullanımıyla çevre kirliliğinin azaltılmasına katkı sağlanacağı ve konvansiyonel ahşap bariyerlerin maliyetinin azaltılacağı düşünülmektedir. İlave olarak çalışmadan elde edilen çıktılar gelecekte farklı türden atık malzemelerin kullanımının önünü açacaktır.

**Anahtar Kelimeler :** Hibrit bariyer, Ahşap bariyer, Çarpmaya Dayanıklılık, Korkuluk, Sarkaç, Atık malzeme, Cüruf, Lastik.
**Bilim Kodu** **:** 91124

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In Conclusion, I hope that this piece of work would be useful and helpful for my own country, and hoping that the government will put it into practice. Thus, I will begive-n the chance to benefit my country and my countrymen.

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## SYMBOLS AND ABBREVITIONS INDEX

### SYMBOLS

$Ep$ : Total potential energy

$m$ : Weight of the rammer

$g$ : Gravitational acceleration

$h$ : Height of the rammer

E : Energy generated in Fy direction

V : Vehicle speed

### ABBREVITIONS

C&D : Construction and Demolition

AASHTO : American Association of State Highway and Transportation Official

DOT : Department of Transportation

NCAC : National Crash Analysis Center

NHTSA : National Highway Traffic Safety Administration

TRB : Transportation Research Board

WSDOT : Washington State Department of Transportation

HVE : Human Vehicle Environment

NASS : National Automotive Sampling System

CDS : Crashworthiness Data System

FRP : Fiber-Reinforced Polymer

GHG : Life Cycle Greenhouse Gas

BOF : Basic Oxygen Furnace

MSW : The total municipal solid waste

WT : Waste Tyre

NCHRP : National Cooperative Highway Research Program

MASH : Manual for Assessing Safety Hardware

ASI : Acceleration Severity Index

W : Working Width

FEA : Finite Element Analysis

# PART 1

# INTRODUCTION

Transportation history is returned to many centuries ago. Emigration of people and transportation of goods from somewhere to another are initiated to growing with creation of wheel. All types of transportation sequence are invented in the nature such as ship in water, vehicle or railway in land and airplane in air. Although, all of the transporter machines are used to human serviceability but side by side of it there are some problems. One of them is traffic accident which has a risk injury or fatal at the life of occupant vehicle and should be regarded as important issue. In 2016, the total number of road traffic fatalities score peak of 1.35 million all over the world based on global status report on road safety, also from 2000 until 2016 while the number of deaths has increased each year, the rate of traffic deaths has abided moderately constant at around 18 deaths per 100000 population as shown in Figure 1.1. Although, this figure shows that number of deaths are increasing but the rate of deaths per population are decreasing due to increasing number of populations annually, development of automobile safety, road safety measures, legal regulations etc. More than half of worldwide road traffic fatalities are pedestrian, cyclist and motorcyclist who are still too often ignored in road traffic system design (geometric design) in many countries [1].

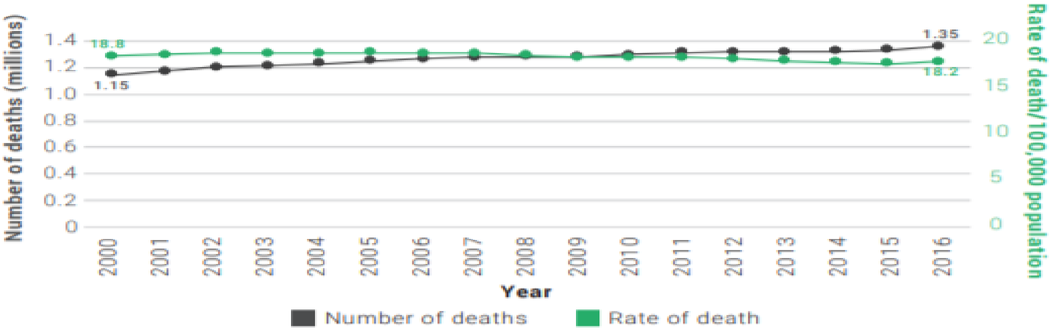



Figure 1.1. Data of road traffic [1].

Also, the majority of accidents involve risk injuries and fatalities or high medical costs caused by obstacles such as trees and road signs on the roadside. The data analysis of traffic accident supported that 34% of the car crashing due to error of the road [2]. Hence, the barrier roadside is used to treat a part of this state, but although roadway departure crashes tend to be severe, particularly when occupants of errant vehicles are exposed to excessive injury hazards at roadside [3-4]. From 50 to 60 per cent of barrier accidents involve injury or fatality, based on reported accident data [5]. The main function of road barrier should be redirect errant vehicle back into the road and provide safety of pedestrian and other road users [5-6]. The energy-absorbing devices on the roadside differ in shape, size, and speed of impact nature [7-8] including steel, concrete, wood or/and hybrid of steel and wood. Steel and concrete barriers can be found in almost all forms of roads. Different types of steel guardrails are widely used worldwide because of their low cost, high capacity for energy absorption, ease of transport and installation, lightness, strength and durability. On the other hand, timber guardrails are also used as more aesthetically appealing choice along scenic paths. In the hybrid barrier wood-steel, the steel roles as a continuous tension component, which retains the rail's structural integrity during a vehicle impact. Unfortunately, timber guardrails are usually expensive due to their use of large solid-sawn timber [9-10]. There are some advantages and disadvantages side of all barrier types compared to each other. Generally, it can be say that concrete rigid barrier and steel guardrail have high acceleration severity and sharp surface respectively [11-12], undesirable accident crash occur while impaction for passenger and vehicle as shown in Figure 1.2.

Figure 1.2. Accident crash of cable, guardrail and concrete barrier [8,12,14].

This research explores methods for improvement designing new roadside hybrid barriers that will use readily accessible low-cost material (e.g. sand, slag and tyre plastic) which covered by wooden and the shape of wood is like F shape barrier, although meet the aesthetic, expense, and engineering needs. For more attractive, it can be used some flower or vegetable at top layer of hybrid barrier as landscape and therefore can prevent oncoming light of vehicle at night driving. The hybrid barrier consists of three main elements; concrete base, sand and wooden part [15-16]. A fundamental momentum based impact study has shown that the natural building material has sufficient potential energy to absorb energy from passenger car on national secondary road [17]. The construction and demolition (C&D) industry realized that most (C&D) waste of source can be extracted, then recycle and reused in infrastructure projects. Now the industry considers recycling and reuse of reprocessed waste as economically viable and feasible. One way of reducing the volume of landfills and protecting scarce natural resources is through the creative reuse of the material in an innovative method. For example, improvement of recycled aggregate concrete for use in sound absorbing concrete barriers [18-19]. With the growing of recycle-process, utilized recycled-plastics as major structural member but from the first it was failed due to unfavorable viscoelastic properties. There are several parameters that should be consider which related to structural quality of plastics such as splitting, creep and excessive bending. In recent years the introduction of newly developed recycled materials enable them to be candidate material for use in the road signs, traffic barriers and energy absorption systems [20]. Thus, use recycle-plastics as a noise barrier which absorb irritant sound [21]. Barriers that use recycle plastic lumbers are not only functional but also beneficial for the environments. There are several advantages to that stuff which it is durable that needs little maintenance, can be cut and fastened like wood, offers many aesthetic alternatives in color and texture, is highly insect and graffiti resistant [22]. Other natural roadside creature is vegetation, which has a potential roles as noise barrier and is environmentally friendly, has a natural sight and is also visually attractive [23]. Furthermore, it has other advantage of the environmental like reduce air pollution of the road [20-25]. With the using any natural material for hybrid barrier it should be consider three main condition that indicate capability of barrier which are impact severity, containment level and working width [26].

# PART 2

## ROAD RESTRAINT SYSTEM

A barrier system is a longitudinal element placed on the sides and median of the roadway to redirect errant vehicle back into the road, reducing the peak acceleration of the vehicle impaction [27-28] safety features to prevent collision with roadside hazards such as poles, trees, obstacles, etc. Additionally, to avoid crash accident vehicles with pedestrian, cyclist and other road users. Also, installing median barrier may rise number of collision but the collision risk is less [29-30]. The improvement of the guardrails from researchers was earlier developed in some countries. In 1920, the USA was the first country initiated the guardrail system. In 1977, American Association of State Highway and Transportation Officials (AASHTO) published “Guide for Selecting, Locating and Designing for Traffic Barriers”, and published the second edition of “Roadside Design Guide” in 2002 [31]. Furthermore, some department and organization have effective role to develop researches, including Department of Transportation(DOT), National Crash Analysis Center (NCAC), National Highway Traffic Safety Administration (NHTSA), Transportation Research Board (TRB) and some university [31-33]. Barrier systems are usually classified into three parts depend on cross large deflection of barrier and dissipate impact energy from vehicle which are Flexible system, semi-flexible system and rigid system as shown in Table 2.1 [31,34].

Table 2.1. Road restraint systems [34].

| Flexible system | Semi rigid system | Rigid system |
| --- | --- | --- |
| • Cable barrier<br>• W-Beam weak post guardrail | • W-Beam strong post guardrail<br>• Thrie-Beam strong post guardrail<br>• Merritt parkway aesthetic guardrail<br>• Steel backed timber guardrail | • Concrete barrier |

**2.1. CABLE BARRIER**

Flexible system is the most common barrier used worldwide than other barrier due to low cost, ease installation and repair quickly. There are different shape, size and structural design according to the impact performance of the road. Example of flexible system barriers are cable barriers and shown in Figure 2.1.

Figure 2.1. Three strand cable barrier [34].

Three strand cable barriers consist of steel cable connected with weak posts which fixed from the soil. The errant vehicle redirects back into the road through tension strength of cable barrier. Currently, most of the research in this subject has been interested on cable median barrier due to its cost effective and well performance to prevent cross median crash [35-37]. The study analyzed performance crash of cable median barrier and G4(1S) W-beam guardrail [38]. It was evaluated that cable median barrier has fewer severe injury and less effective to prevent penetration during impaction as compared to G4(1S) W-beam guardrail. There are several issues that influence the property of cable barrier such as the distance between posts, the durability of the posts and the tension strength of the cable. In another study, the maximum lateral displacement of the cable decreases when the initial tensile force increasing or distance between the posts decreasing but ASI of the vehicle increases when increases initial tensile force and decreases then increases when distance between posts increases [31]. The main advantages of cable barrier are low cost, ease of construction, repaired rapidly, more aesthetically than other barrier, redirect different size of errant vehicle and low (ASI) of vehicle occupants [39]. The Washington State Department of Transportation (WSDOT) in 1990 became to develop a median barrier in place where 30 feet wide to decrease the severity accident of the median so decided to use cable median barrier as economy barrier for this location and evaluated the barrier by sponsoring crash test according with NCHRP report 350 [40]. The dynamic deflection of test result was less than 12 feet. One problem of cable median barrier is the vehicle which under rode the cable barrier and cross to opposite traffic-lane, so the researchers focused on the parameters that causing underride vehicles with one of the standard cable barrier designs which is Washington three-strand cable barrier design [41]. They used computer simulation with nonlinear (FE) model to evaluate performance of cable barrier that reduce cost and time of the tests [42-43] and validated by full-scale crash test [44-46]. The vehicle dynamics analysis for example Human Vehicle Environment (HVE; The engineering dynamics corporation) is utilized to create 3D models of vehicles, environments and dynamic interaction between vehicle and barriers. Three types of car developed with different shape in order to select optimum position of cable barrier. It determined that 0.3 m away from center of sloped terrain is optimum position to redirect and prevent underride vehicle. Generally, the advantages of cable barrier are low installation cost, decreased installation prices, decrease deformation on errant vehicle, higher visual appeal and larger sight distance. Although, the disadvantages are ineffective for noise traffic absorption, higher damage cost, larger deflection so need greater offset distance behind the barrier as compared to other barrier to contain or redirect errant vehicle if not there is no efficiency of cable barrier, re-tensioning required occasionally and needing faster repair due to its ineffective after impact [47]. Cable barrier has same problem with steel guardrail which is motorcycle-crash. The posts are fixed along the road to carry the wire rope but cause too much danger and risk injury or fatal motorcyclist than other barrier collision while crashing motorcycle-barrier. Although, there has been no comprehensive study about cable barrier safety with regard to motorcyclist [48].

## 2.2. STEEL GUARDRAIL

Steel guardrails are classified into flexible barrier system and semi rigid barrier system. Steel guardrail of flexible system consists of W-Beam (weak post) barrier which characterized by larger dynamic deflections in a collision, considered more forgiving compared to other stiffer barrier [49-50] and it is also act as cable guardrail like posts role to mount the rails and redirects errant vehicle through its tension strength as shown in Figure 2.2.

Figure 2.2. W-beam weak post guardrail [34].

The proposed design of weak post W-beam allows to fail bolt connection during impaction and separate rails from posts in lieu of being dragged by the post to the ground because this action permits the rail to stay in contact with errant vehicle and rolling as cable barrier to redirect vehicle [51-52]. The second type of steel guardrail is classified to semi-rigid system which is characterized by less deflection and higher acceleration level due to less energy dissipate than flexible system [53]. Semi-rigid barriers are block-out W-Beam (strong post), block-out Thrie-Beam (strong post), Merritt Parkway Aesthetic Guardrail and Steel-Backed Timber Guardrail as Shown in Figure 2.3.

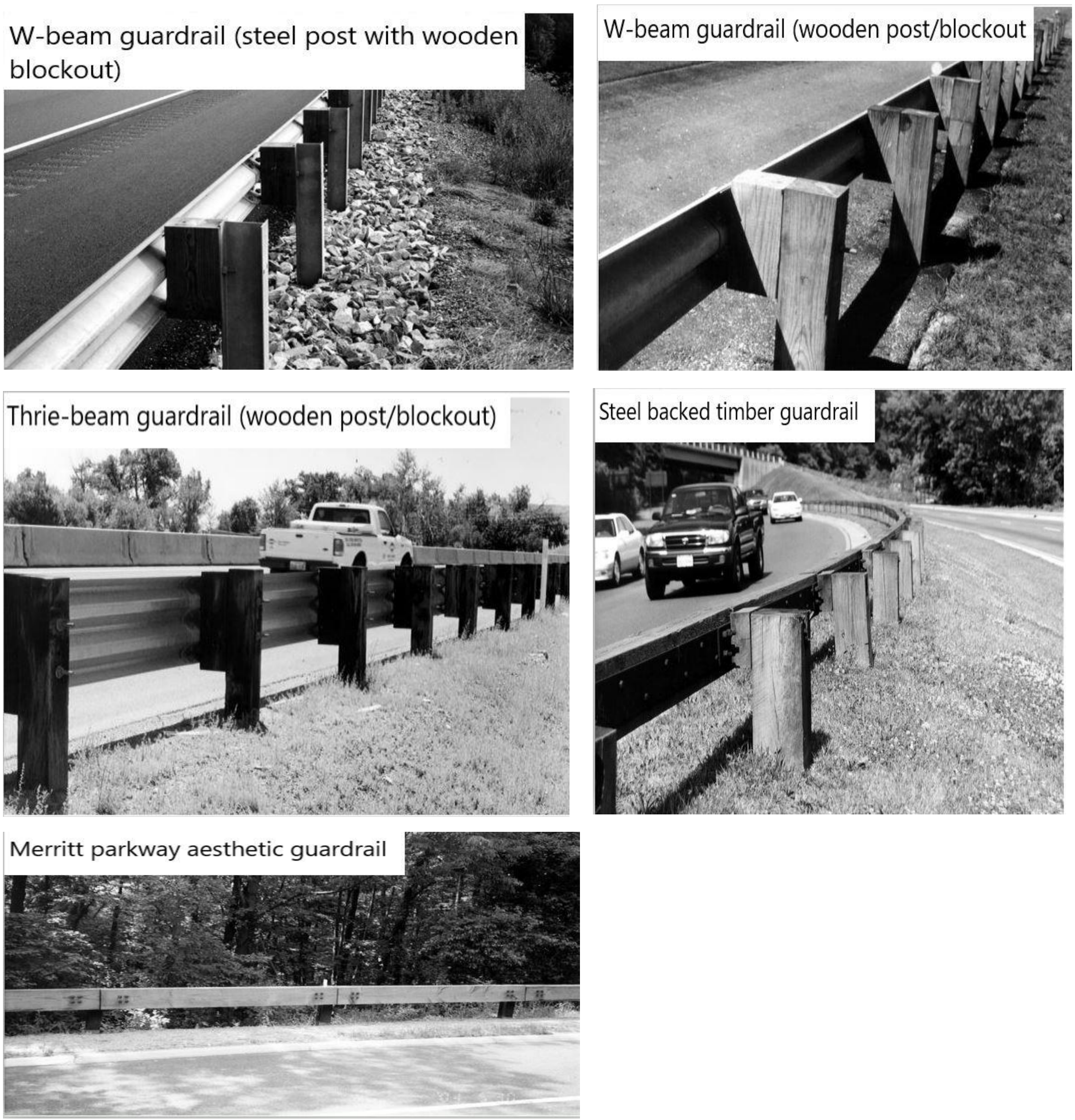



Figure 2.3. Various steel guardrail types [34].

Block out W-beam guardrail (strong post) is the most common barrier use in today [54]. It consists of W-beam rail with 1) steel or wood post with wood or plastic block or 2) steel post with steel block). Strong post W-beam guardrail redirect and contain errant vehicle through energy absorption by rail deformation and post deflection in soil [55]. Due to inadequate structural detailing wheel snagging occur on critical point such as strong post in the guardrails [41,56]. In consequence, the vehicle decelerates suddenly, decrease its stability and initiate to roll. One of the factors that reduced or prevented the tendency of wheel snagging on strong post is using offset blocks which isolate the posts and wheel of the vehicle during impaction and absorb energy more efficiently. Also, the impaction of weak post W-beam guardrails are more safety than strong post W-beam guardrail. Furthermore, there is a comparison analyzing between 212 weak-post crashes and 1045 strong post W-beam guardrail crashes. Weak post W-beam crashes consist of 1.9% fatal, 10.8% hospital and 87.3% other, whereas strong post W-beam crashes consist of 3.3% fatal, 15.8% hospital and 80.9% other [51]. Although, currently steel guardrails used in all over the world due to their low cost, sufficient energy absorption, feasible of carrying and placing and durability. But the disadvantages of W-beam guardrails are cost maintenance, zinc emission, no noise traffic absorption/prevention of oncoming traffic light, difficult to replace and high-risk injury while motorcycle W-beam guardrail crash. Especially, the post of the guardrail tends to much severe for motorcyclists because of if the motorcyclist involved accident and lose his/her control either strike at top of post, or tumble and slide along the guardrail with impact at the bottom of the post as shown in Figure 2.4. So, motorcycle-guardrail crash is the most harmful event rather than passenger vehicle-guardrail crash [57].

Figure 2.4. Motorcycle crash accident with sharp surface of guardrail [8].

Also, end of the guardrail is another risk of the life of occupant. According to the National Automotive Sampling System (NASS) crashworthiness data system (CDS) in USA during 1997 to 2008 the average crash of guardrail was 51000 crashes annually. But the odds of crashes with the end of guardrail about 6600 or almost 13% each year [58]. The end of the guardrail should consider well, because while impaction strike and penetrate vehicle occupant compartments as shown in Figure 2.5 and induce to risk injury or killing the occupants [59].

Figure 2.5. Guardrail penetrated the vehicle [59].

To the prevent or reduce risk injury of the end of guardrail and to either redirect or stop the impacted vehicle safely, new terminals are designed. Guardrail end terminal are designed to energy and non-energy dissipated. The energy dissipated is designed to slow vehicle impacted and even stop it completely through absorbing sufficient energy. But non dissipated energy just is designed to avoid guardrail from penetrating without slowing the vehicle. Also, End terminals are developed and designed to flared and tangent. The flared design which mean offset of end terminal typically by three to four feet from face of the guardrail as shown in Figure (2.6.a) but in the tangent design, end terminal is at or near same line of the guardrail as shown in Figure (2.6.b) [58].

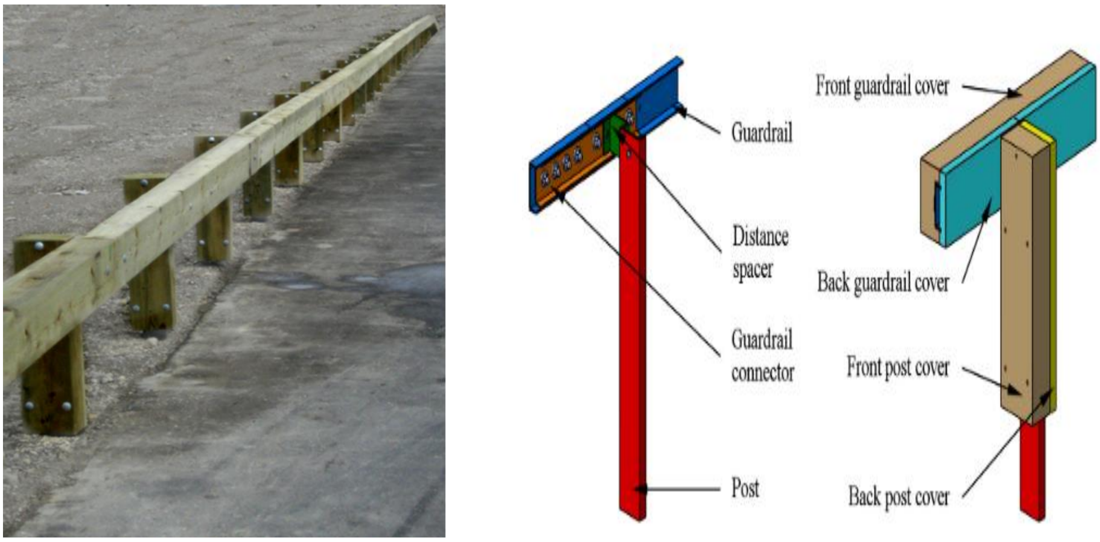
(a)

(b)

Figure 2.6. (a) is non energy dissipate (b) is energy dissipate [58].

## 2.3. WOODEN BARRIER

Wood is one of the common materials that use in roadside safety barriers. Plain wood due to its low tension and brittle failure mechanism, it is not common suitable material that acts as guardrail beam. With the using timber barrier is often used steel which acts as continuous tension, flexural member and provide structural integrity of the rail while vehicle striking. Generally, two kinds of wooden barriers are used in the world; first, the posts are wood and main body is steel, secondly, the posts are steel but the main body is wood. Additionally, in some cases reinforced wood by steel or fiber but there has not been common all timber guardrail yet. The main advantages of wooden barriers are more environmental friendly, provide aesthetic alternative along the road and make harmonization with around scenic terrain [60]. Especially, appropriate with historical places, natural rural road and heritage zones, etc. But disadvantages of wooden barriers are expensive due to their large solid sown-timber and need sufficient crew or crane for installation [8]. Wooden barriers most commonly used in posts and block-outs of guardrail system because it is better than steel due to its relatively low strength and large cross-section. The increased surface area and lower strength of the posts develop large soil reaction and decrease snagging potential respectively while steel post is not possible for this function [61]. Steel guardrail especially W-beam guardrails are the most common barrier that used among the barriers due to their reliability, cost effective, ease of installation and durability while timber guardrail is more expensive because of its heavy and difficult for installation therefore need numbers of worker or track mounted crane [9]. Although, wooden guardrail is more aesthetically pleasing alternative therefore used along landscape road in order to make harmonization with the surrounding scenic districts [60, 62-63] (historical area, heritage zones, mountains, etc.). As discussed earlier, wooden guardrail has not enough tension strength to restrict errant vehicle so used steel backed timber because of steel can provide enough tension strength which transfer tensile stress to the posts and maintain safety of road during impaction such as merritt parkway guardrail [63]. Such reinforced wooden barrier cover or conceal load carrying steel core as shown in Figure 2.7. which bolt connection is used to connect load carrying parts that have a significant act during impaction [64-67]. When the vehicle impact guardrail the bolt connection between posts and guardrail must fail to avoid dropping of the guardrail due to post deformation while the bolt connection must not fail between wooden parts and steel core because of increase the severity of impact due to mutilation of large and heavy guardrail wooden parts [68].




(a) (b)

Figure 2.7. (a) Wooden barrier reinforced by steel, (b) (left) Structural steel profile, (right) covered by wood [68].

It is used EN1317 standard with TB32 to evaluate the performance of the barrier, the result showed (ASI= 0.61 and W= 2.02). Also, full timber guardrail was developed as shown in Figure 2.9. In the purpose of reduction of zinc emission of steel barrier and more environmentally friendly but 20% cost more than steel barrier [69].

Figure 2.8. Timber guardrail without reinforcing [69].

It is designed two rail element bottom and top, the bottom rail is designed to small car to obtain low ASI during impaction which connected to steam bent timber. While, the top rail element is designed to withstand a bus impact which connected to piles. By numerical simulation (MADYMO) and full-scale crash test have been successfully tested, fulfill all requirements in EN1317 for both small vehicle and bus and the ASI of the test was equal to 1. This system was practiced in Netherland. For aesthetic reasons, timber guardrails are installed along scenic road and considered more attractive pleasing than steel guardrail. Well landscape guardrail can provide attractive view along road and user-friendly environment. In the purpose of attaining coordination of guardrail with surrounding landscape district and reflect native ecological. The steel backed guardrail is designed which can achieve 360°-view landscape reflect with considering material and cost saving. It consists of beams and columns, in the purpose of process feasibility and decrease timber wasting as cost effective the following cross section of the column and beam are selected [60] as shown in Figure 2.9.


.

(a) (b)

Figure 2.9. (a) Side view of beam, (b) Top view of column [60].

Because the system consists of two beams, the lower beam can also act as block-out. Figure 2.10 illustrates developed steel backed timber guardrail.

Figure 2.10. Aesthetic timber guardrail reinforced by steel [60].

The designed system resist large vehicle and redirect errant vehicle back to its direction by 91 cm maximum dynamic deflection of steel backed wood landscape guardrail. Large solid-sawn timber and using steel to transfer tensile stress are expensive due to its heavy of timber and steel that need large crew or crane to installation. So, researchers need to find an alternative material instead of steel at the same time play the roll of steel. Lightweight and inexpensive timber guardrail is developed by utilizing Fiber-Reinforced Polymer (FRP) which serves as tension member. Used hardwood red maple as shown in Figure 2.11 and reinforced with 3.5mm thick E-glass FRP. In the past, successfully reinforced softwood glulam beams by using  epoxy and FRP. The researchers used computer simulation to study effect of specimen geometry and amount of FRP, they indicated that when (d =156 mm) its similar to Merritt Parkway Guardrail. Whereas, it responded most similarly to W-beam rail when d=76mm. Also, better ductility attained with increasing ratios of FRP volume to wood volume [70].

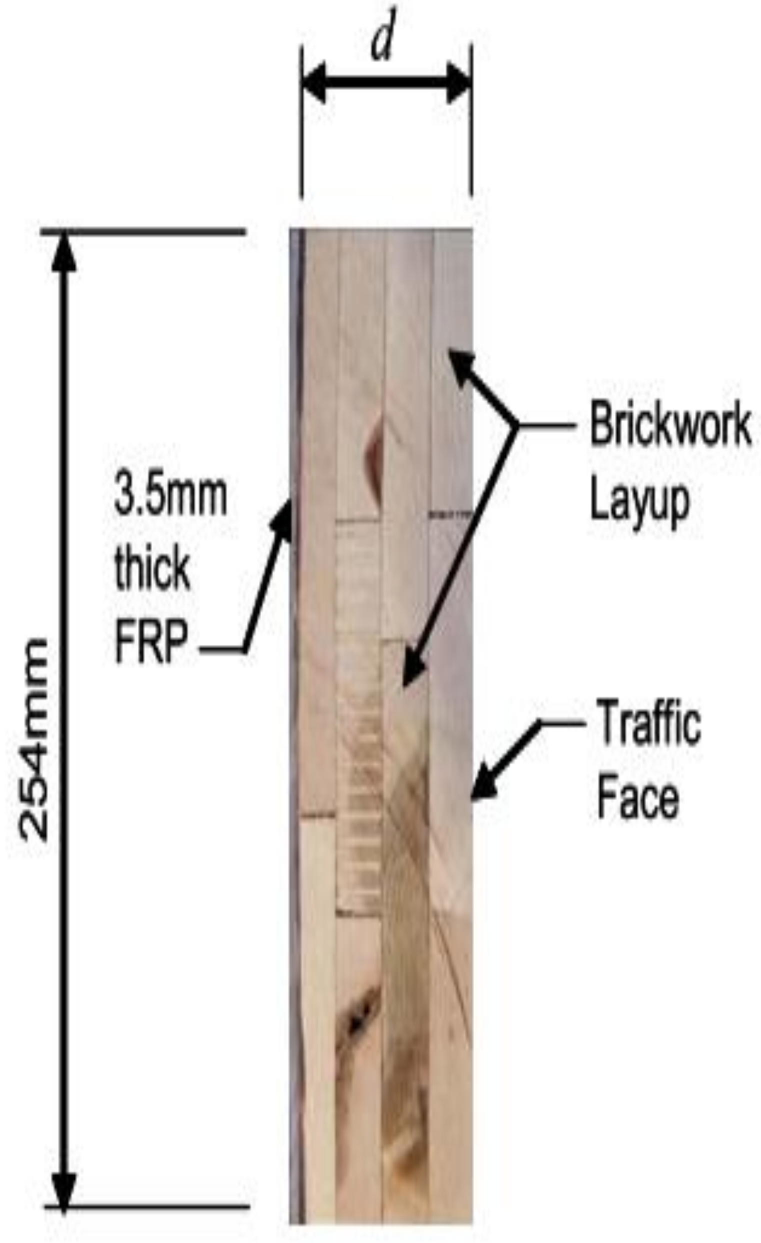



Figure 2.11. Timber guardrail reinforced by fiber [9].

## 2.4. CONCRETE BARRIER

Concrete barrier is classified as rigid system. This system barrier is characterized by high ASI on the one hand, and low deflection value on the other hand than flexible and semi rigid system [62,71]. Figure 2.12 illustrates concrete barrier.

Figure 2.12. Rigid concrete barrier [58].

Flexible or semi rigid barrier dissipate energy and decrease acceleration by deformation and plasticity in the material but concrete rigid barrier dissipate energy by shape, mass and friction with the surface of the road [72]. The advantages of concrete barrier are long service life without too much maintenance required, it has portable type which can be replace where need to install, used in narrow median and bridge decks due to its small deflection [73-75] and has less risk injury of motorcyclist collision than W-beam guardrail due to its shape [76]. But the disadvantages of concrete barrier are high cost to transportation / installation due to their solidity and its rigidity / friction between surface of the ground and concrete barrier causes to highly risky (injury or fatal) at the time of impaction [12,77]. Although, impacting concrete barrier or has less injury as compared to fixed roadside obstacles [78] but in the vehicle collision cable barrier is more safely and less resistance than concrete barrier or thrie-beam guardrail to redirect errant vehicle [73]. Currently, Concrete barrier consists of four major kinds in USA: F-shape barrier, New Jersey barrier (NJ), single slope barrier and vertical barrier as shown in Figure 2.13.

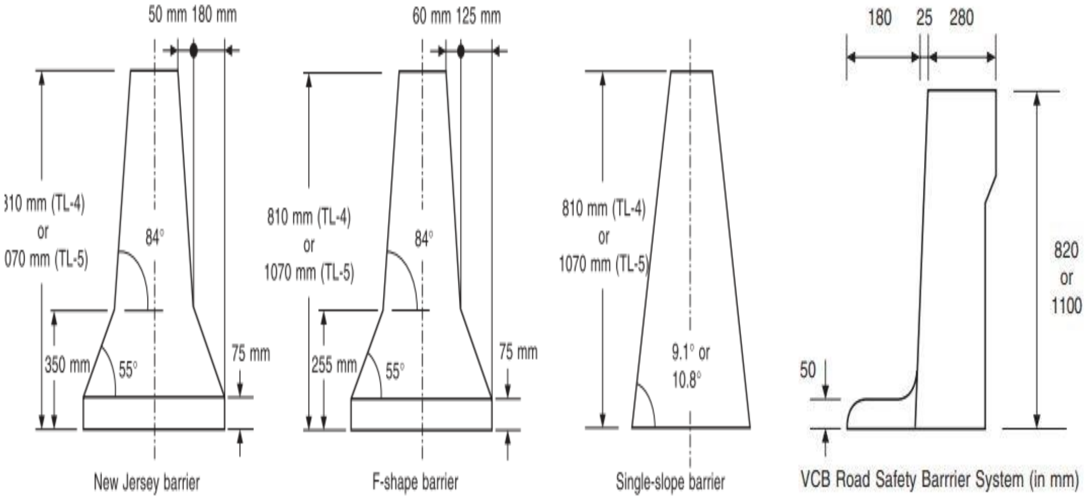



Figure 2.7. Various concrete barrier profile [79].

The New Jersey concrete barrier is the most common barrier used due to its cost. While, F-shape barrier is better than (NJ) with respect to roll over for small car [79-80]. Because of F shape barrier, New Jersey barriers have a poor resistance for heavy good vehicles while impacting which it causes to risk injury or fatal on highway overpass bridge. Many researchers evaluated or developed concrete barrier by utilizing finite element method(FEM), especially LS-DYNA and ANSYS program, to simulate concrete barrier and vehicle [81-86], FEM is used to develop portable concrete barrier and stiffening pin-and-loop joints of F-shape barrier because of the concrete segments can not remain stably and vehicle collision leading to introsion work zone area of barrier, three design modification (tapered shims, seperator block and steel cover plate) applied in FE simulation [87] and compared with unmodified design(Baseline), it is found that the tapered shims design decreased the deflection by approximately 13%, while the cover plate and the separator block designs performed similarly and decreased the deflection by 38%. Consequently, this reduction in deflection also decreased the impact severity to the vehicle and its occupant. The studies also find effect of segment length (2,4,6,8m) of concrete barrier on ASI, working width and dynamic deflection by perform TB11 (900kg, 100km/h, 20 degree) accordance with standard EN-1370 [88]. It is found that with increasing segment length of concrete barrier proportion increase ASI and decrease working width with dynamic deflection as shown in Table 2.2 [88].

Table 2.2. Effect of segment length on (ASI, working width, dynamic deflection) [88].

| NO. | Concrete barrier composed of segments | ASI | Working width (m) | Dynamic deflection (m) |
|---|---|---|---|---|
| 1 | 2 m | 1.24 | 1.69 | 1.14 |
| 2 | 4 m | 1.37 | 1.07 | 0.52 |
| 3 | 6 m | 1.44 | 0.85 | 0.3 |
| 4 | 8 m | 1.45 | 0.79 | 0.24 |

## 2.5. PLASTIC BARRIER

Using plastic as roadside barrier is not appropriate due to its weak tension and flexural strength [89]. But it can be used as a part of the barrier such as using steel guardrail with plastic block-out or in portable water-filled barriers (PWFBs), it acts as a shell [90] as shown in Figure 2.14 or recycled and mixed with additive material. But, there advantage of recycle plastic  such as little repair needed, absorb noise traffic, forgives appealing alternative in both color and texture [22].

Figure 2.8. Example of portable water filled barrier covered by plastic [22].

## 2.6. OTHER MATERIAL

Presenting roadside barriers are usually not aesthetically appealing and high cost to install and maintain. Engineers often interest to develop safety and structure requirement of barrier without consider aesthetic side. The only alternative barrier that use in Europe which meet aesthetics and attract is mixed of steel guardrail and timber but although it is more expensive than concrete barrier and steel guardrail [11]. Therefore, alternative low cost and aesthetic barrier is needed. Using natural material can be used as a key of low cost of maintenance, installation and landscape [17]. Examples of natural material such as earth, stone and etc. One of developments of natural material is gabion barrier which is also economical and landscape but it sometimes needs maintenance [11] as shown in Figure 2.15. Although, a review of scientific literature in US and Europe exposed very little prior study on the utilize of natural material for roadside barrier than steel and concrete [17].

Figure 2.9. Gabion barrier [11].

Gabion barrier is evaluated by full scale crash test, the test was conducted under TB31 condition and the result of the test was un accepted due to roll over of vehicle, large displacement (3.4 m) and ASI was (1.3 m/$s^2$) [11]. The test is shown in Figure 2.16 and 2.17.

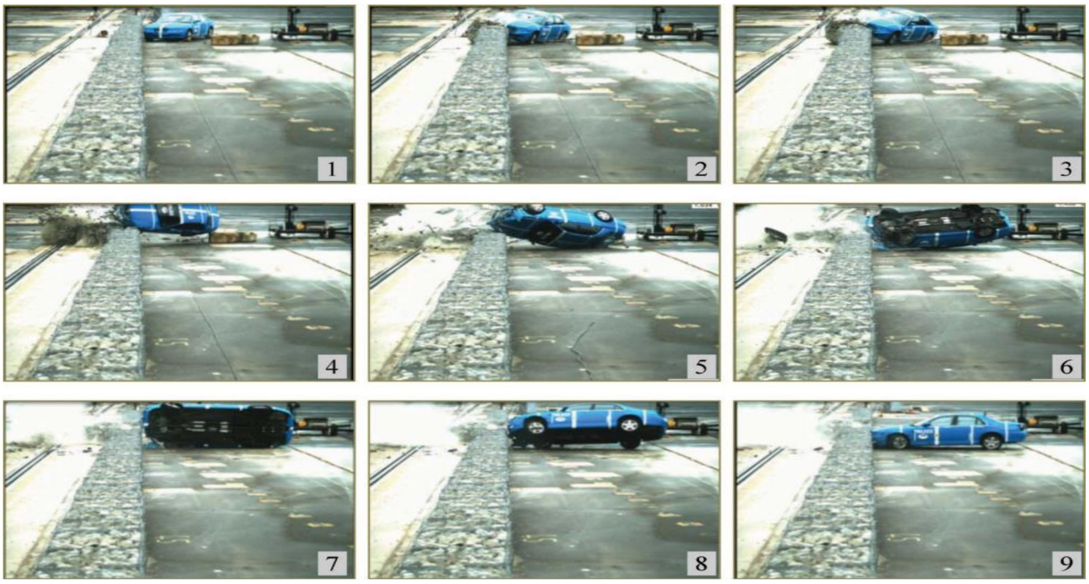



Figure 2.16. TB31 full scale crash test (Top view) [11].


Figure 2.17. TB31 full scale crash test of gabion barrier [11].

Recycle materials is other feature material that have effective cost and sound absorbing such as using recycled plastic bottle in roadside safety barrier [7]. Because one of the factors that should be consider and take in the highway design is noise barrier [89]. Flexibility and thermal expansion coefficient of Recycle plastic lumber is more than wood and also it is more stronger to resistance changing temperature [22]. When road restraint system is applied, it should be considered some issues such as environmental, landscape, noise sound and structural requirement. Environmental side of barrier such as Life Cycle Greenhouse Gas (GHG) emission and carbon emission of wooden barrier are less and more environmentally friendly than concrete and steel barrier due to its zinc emission [69]. Therefore, the development area of wooden barrier should be increase [91], because there is no enough review on using natural material in road barrier system, in this study prescribed parts of hybrid barrier (steel, wood and concrete) in detail.

In order to fill gaps among all types of barriers, a novel design barrier called hybrid barrier was designed by applying all issues of structural requirement, aesthetic and environmental. The hybrid barrier system design consists of three main parts: wood, sand and base concrete. Base concrete insulates wooden from water and insects because of its sensitivity, F-shape as concrete barrier but made of wood with filling by sand. Sand is used as potential material to absorb impact energy at the same time as economy material usage and wood make the barrier more aesthetical. Steel which connects base concrete with wood. Also, at the top of hybrid barrier will be placed some flowers to prevent or decrease the severity of light of transverse side and can remain green for all seasons of year. The wooden part and plant will attribute the hybrid barrier more aesthetically and make harmonization with surrounding area. Because of the earlier studies, developed road restraint system in term of structural requirement to withstand impact load from the vehicle without perspective considering of aesthetic, cost and environmental together. So, this new design barrier considers all of them together, especially landscape side which can be used in historical, touristic and mountain place that has not done before in the literature. In recent year, it is noted that the percentage death of traffic in the world is increased due to increasing mobilization. Also, waste material is other problem among all of the world due to excess of industrial and technological development. So, using waste materials in a barrier system have not discussed in the literature widely. Therefore, any studies to decrease or prevent this problem should be supported.

In this study, it is utilized waste material (slag and tyre) in the hybrid barrier instead of sand in the purpose absorb impact energy. It is considered that using waste materials as roadside barrier have not been applied yet. By fulfilling requirement of

EN 1317 the performance of hybrid barrier by using waste materials were calculated and compared by conducting pendulum crash tests. The aim of this approach is to using recycle waste material (slag and tyre) as cost effective and environmentally friendly. Furthermore, the shape of this new barrier will contribute to decrease risk injury and fatality for occupants especially motorcycles.

# PART 3

## HYBRID BARRIER DESIGN AND MATERIAL PROPERTIES

Hybrid barrier is a barrier that apply all issues of road restraint system like structural integrity, landscape, cost effective and environmentally friendly. Through sand it can be absorb sufficient impact energy from vehicle by minimum damage of vehicle and risk of occupants [15]. In addition, using sand as energy absorber decreases the cost of hybrid barrier. Also, wood is used as cover of sand by connecting with steel and putting some flowers at the top layer of hybrid barrier in order to apply aesthetic and environmentally friendly sides of road restraint system [92]. The wooden parts connected to concrete base via steel profiles. Generally, the shape of hybrid barrier based on F-shape concrete barrier as shown in Figure 3.1. The elements of hybrid barrier are discussed below.

Figure 3.1. Design of hybrid barrier.

## 3.1. WOOD

Wood is the main element that provides integrity and crash resistance of hybrid barrier. Furthermore, it exposes an aesthetic hybrid barrier and environmentally friendly. The benefits of using wood are workability, the ability of varnish/paint, high carbon stock capacity, high shock absorption, high strength compare to its density, heat and noise absorption [93-96]. In the literature, the disadvantages of wood are expensive due to its large solid-sawn that need crane or large crew and also low tension and brittle failure mechanism. But in this study, considers the cost of the timber by using segmental of wood and utilizing natural material (sand, tyre and slag) to support the wood and absorb impaction. Although, the cost of hybrid barrier differs depending on the quality and type of the wood and also the thickness considered to be utilized. Hence, Fir (Abies nordmanniana subsp. Equestrianism) timber was chosen as a timber of hybrid barrier due to its availability in the area and cheaper as compared to other kinds of wood. In the purpose of avoiding from visual pollution and deformation which may be appear from joints due to shrinkage and swelling cycle of the fir timber, utilized rubbed joining technique to fix fir timber on metal profile. The prepared dimensions of each segment of the fir timber are (40 mm thickness* 100 mm width* 1250mm length). The edges of first segment (at the bottom) are tilted to fit with base concrete and edge of second segment but the edges of (3, 5, 6, 7) segment are cut to fix with each other and segments of (8,9) are shaped as (1, 2) segments as shown in figure 3.2. The diameter of 3.5 mm screw is used to fix fir timber onto metal profiles. in order to be high quality and efficiency of the screwing process, the pilot hole drilled up to 80 percent of the screw diameter [97]. Accordingly, in this study before the screwing operation, the pilot holes were drilled on the fir timber up to 80 percent of the screw diameter. Each hybrid barrier consists of 18 segments of fir timber 9 segment for each face. Each segment is mounted on the metal profile by 4 screws. So, the total number of screws that use for each hybrid barrier are 72 screws.

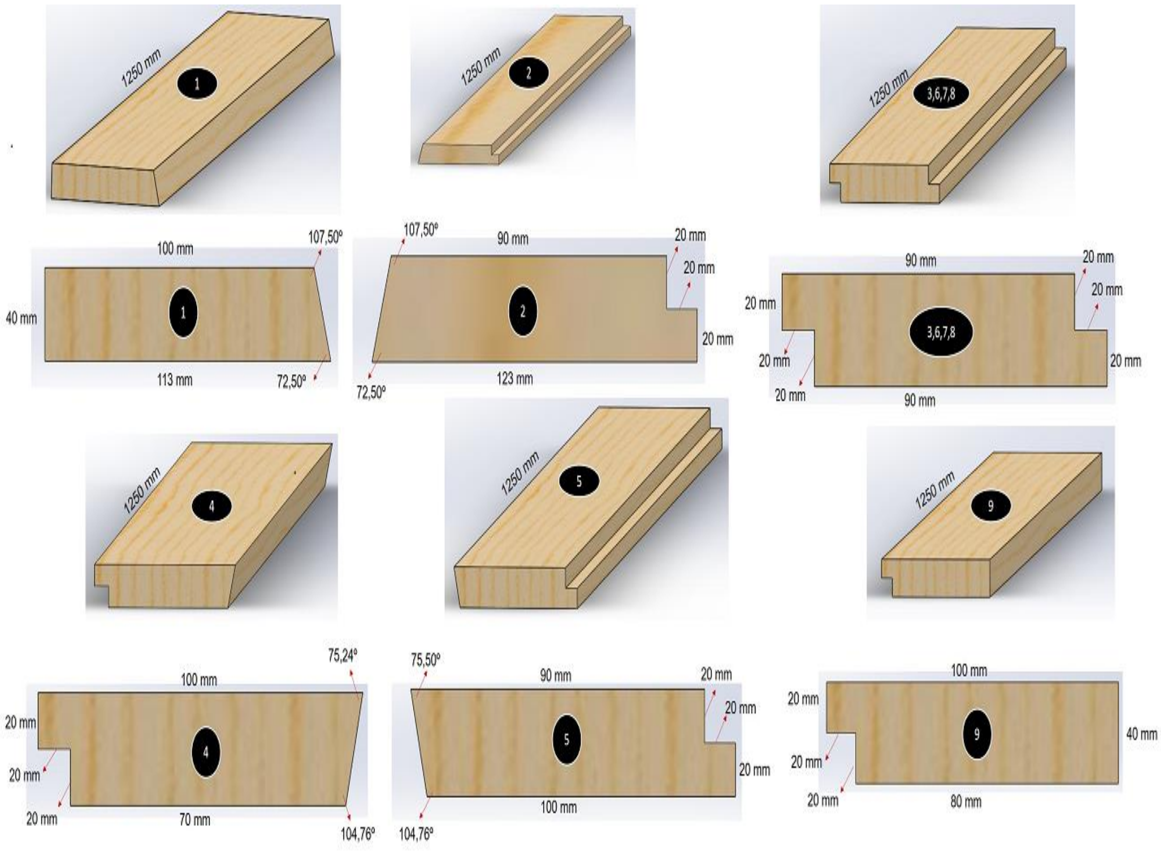



Figure 3.2. Dimensions of segment timber

### 3.2. CONCRETE BASE

The main purpose of using concrete base to preserve the wooden part of hybrid barrier from the run of or water of the pavement. Also, concrete base participates to absorb energy by friction with the surface during vehicle impaction but in this study is not considered. The dimensions of concrete base of hybrid barrier as shown in Figure 3.3. It has two lateral gaps as dimensioned by 100 mm to pass the water from the road to edges. Also, there are four holes (21*41mm) of top surface of concrete base which are the place connection of metal and concrete base. Furthermore, the male and female parts are the connection of concrete base which fix concrete bases together and transfer load from each to other during striking.

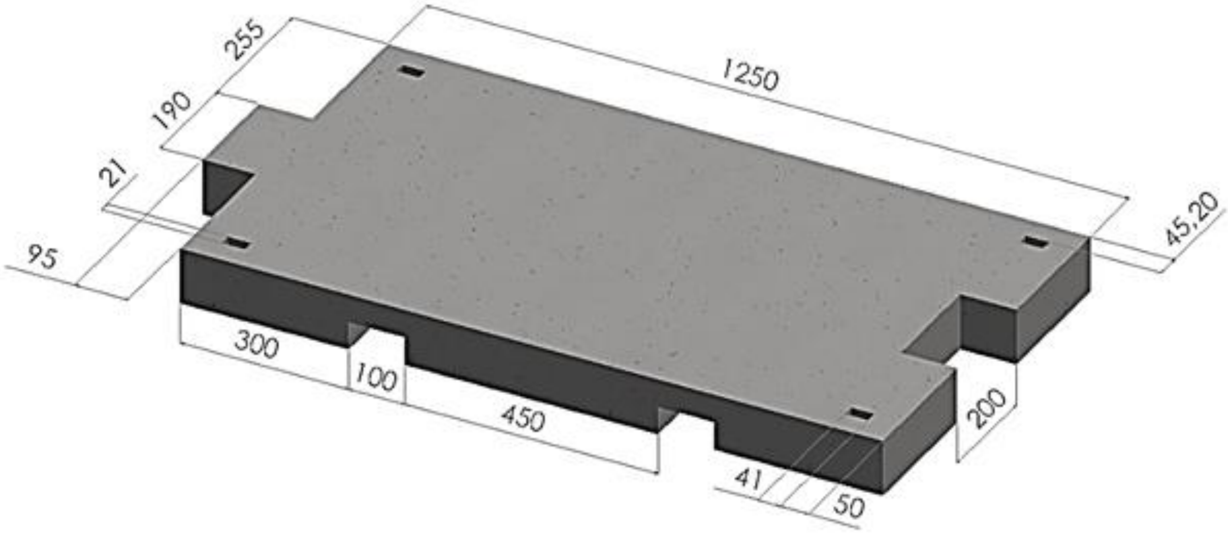



Figure 3.3. Concrete base of hybrid barrier

**3.3. STEEL STRUCTURE**

Steel profiles are the elements which provide basic shape of the barrier and timber segments are mounted and overlapped on by fixing horizontally on two steel profiles via screws. For each hybrid barrier two metal profiles are used. The shapes of metal profile are based on F-shape barrier and the dimensions of metal consist of box profile (20*40mm) with thickness of 3 mm. Figure 3.4 illustrates profile and dimension of metal steel. Through the holes of top surface of concrete base, the steel metals are fixed and each segment of metal steel is connected to each other by welding.

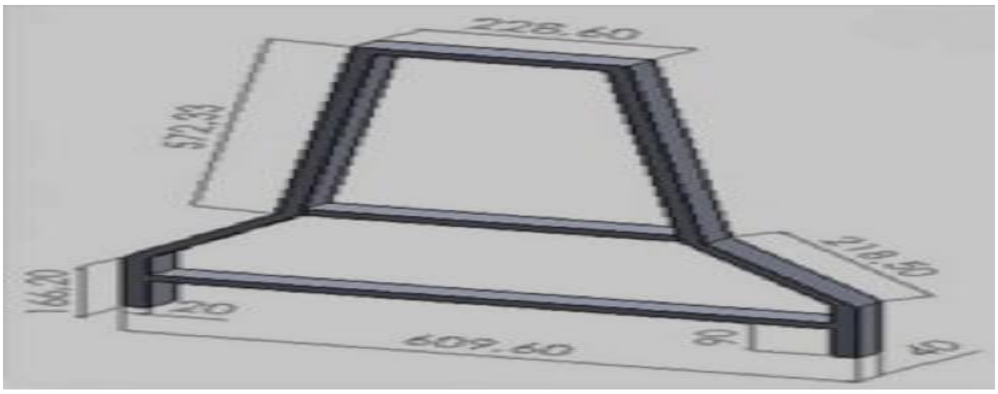



Figure 3.4. The connector element of hybrid barrier (Dimensions in mm).

In this study, three segments of hybrid barrier are designed to test experimental crashes. Accordingly, Steel profile of each hybrid barrier is connected to its adjacent through using four steel rod and fixed by the nut in metric 12 dimension, as shown in Figure 3.5a. By this way, beside the connection of male and female of the concrete bases, the connection of steel profiles of each hybrid barrier to each other via steel rods are purposed to transfer the applied energy among the whole barrier rather than a specified point during the time of the collision as shown in Figure 3.5b.


Figure 3.5. (a, b) Connection between metal steels.

### 3.4. SAND MATERIAL

Recently geo-material are been a commonly utilized material in engineering application ranging from military until construction usages [98]. For instance, sand is one of the  widely used material of construction components in both civil engineering and military application due to its potential energy [99], which characteristic to its easy procurement and cost-effectiveness [100]. It is a granular material that classified as soil textural and composed of crashed rock and mineral particles. Particle size of sand ranging between (0.075 – 4.75 mm), so it is known as fine material which finer than gravel and coarser than silt, and its specific gravity ranging between (1.5 – 1.8 ton/ $m^3$). The characteristic of sand differs due to physical or chemical effective. For example, sand is became cohesionless when moist saturated or dry, but it has confident cohesion with optimum moisture content [101]. Although, the study indicates that dry sand is less compressible (more stiffness) than moist saturated, because of moist saturated sand may induce to softening and consequently pore water roles as lubricant among particles that induce to reduction in shear loads [98].

In this study of hybrid barrier, sand is selected as primary energy absorber material rather than wood and concrete with particle size of ranging between (0.425 – 4.75 mm) and specific gravity of (1.6 ton/$m^3$). Because of studies in the literature indicate that sand has a high potential energy to absorb kinetic impact energy during collision [102-105]. furthermore, ability on stress wave diminution and energy absorption allow the sand proper apply vibration isolation and blast mitigation [100]. In the purpose of the sand is not scattered onto the road during impaction and cause other accident in the surrounding area, the sand is inserted in sandbags as applied in the experimental crashes too. Figure 3.6 shows sandbags of hybrid barrier.

Figure 3.6. Arrangement of sandbags of hybrid barrier.

## 3.5. WASTE MATERIALS

Waste is characterized as any material which created by humans and industrial activity that does not have any remaining worth [106]. Environmental problems have been considered as dangerous state in the construction and its protection had been indispensable hardly in all over the world, it appears difficult to protect environmental from construction activity. So, the most effective method to recover those waste product are; reuse, recycling and reduce the wastes [107] and as shown in Table 3.1.

Table 3.1. Percentage of waste and recycling [108].

| Region | US | EU-28 | Gulf Co-operation Council (GCC) |
|---|---|---|---|
| Population in 2010 (million) | 310 | 501 | 40 |
| Total solid waste (million ton/year) | 380 | 2742 | 120 |
| Tire rubber waste (million ton/year) | 20.53 | 28.92 | 3.6* |
| Tire rubber waste (ton/capita/year) | 0.066 | 0.058 | 0.09 |
| Recycled tire rubber (million ton/year) | 17.86 | 20.04 | 0.66 |
| Tire rubber waste/total waste (%) | 5.40% | 1.05% | 3.0% |
| Recycled tire rubber (%) | 87.0% | 69.0% | 18.3% |

Humankind currently produces two billion tones of waste annually between 7.6 billion people according to Global waste index (2019). The world bank announced that global annual waste production is suggested to increase to 3.4 billion tones over the next 30 years, up from 2.01 billion tones in 2016. The data Indicates that from 2010 to 2016 plastic production in all over the world increased by 26% from 334 to 422 million tones [109]. Furthermore, nearly 1.2 billion tyres are discarded in all over the world [110]. The total municipal solid waste (MSW) generated in the USA was 292.4 million tons in 2018, and almost 69 million tons of the MSW were recycled, nearly 25 million tons were composted. That equals to a 32.1 percent recycling and composting rate as seen in Figure 3.7.

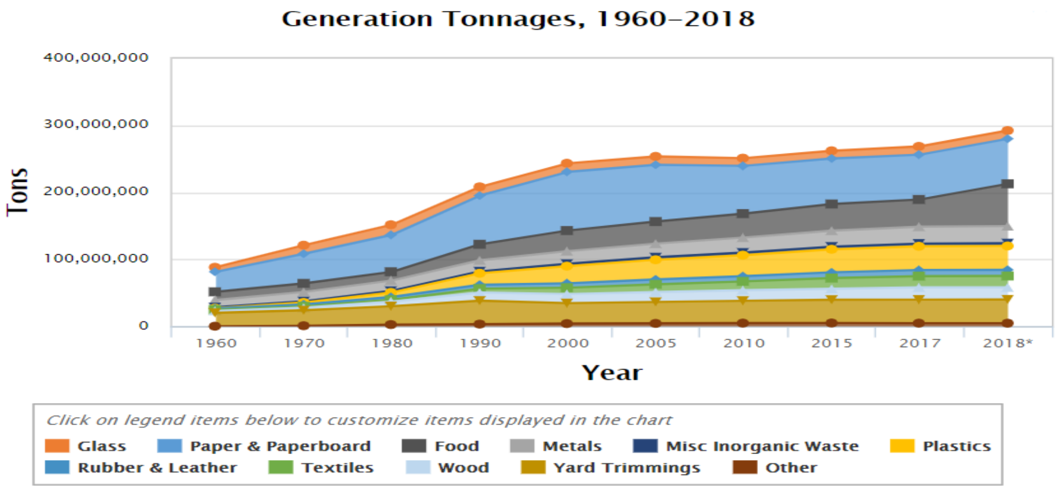



Figure 3.7. Increasing amount of MSW annually in USA [111].

The large amount of waste material has a dangerous risk on the life of people environment. Hence, it should be considered and solve this problem. Recycling waste material is one of the strategies in decreasing of waste, which provide three benefits: (1) economic benefits, (2) environmental benefits and (3) public health and safety benefits[112]. It can be list waste materials as concrete (foundation, slab, beam, column, etc.), brick, masonry, paper, ferrous and non-ferrous metal, wood, plastic, glass, pipe, wire, roofing, rock, soil and etc [107]. But in this study, it was tried to use two kind of waste materials in lieu of sand. One of them is slag and the other one is waste tyre. These are the easiest for procurement and economic for this district but more kinds can be applied.

### 3.5.1. Steel Making Slag

Slag is the waste product of iron and steel manufacture process which are classified into blast-furnace slag (iron making slag) and steel-furnace slag [113]. Iron slag is the non-metallic product composing basically of calcium silicates and other rests that is improved in a molten state coincidental with iron in blast furnace [114]. While, Steel slag is the oxidized material that is produced from mixed of dolomite, lime, and other auxiliary materials, and pig iron of blast furnace is blown onto by oxygen to eliminate sulfur (S), phosphorous (P), carbon (C) and other components to generate raw steel in a basic oxygen furnace (BOF) [115].

As earlier as 1880, Usage of waste slag began with Europe for phosphate fertilizer because of its chemical composition [116] and for soil improvement and plant growth [117-118]. In addition,  because of its mechanical and physical properties such as roughness, adhesiveness, toughness, hardness and wear-resistance, it can be used instead of aggregates for hydraulic structure and road [119-122]. Furthermore, it can be utilize for wastewater treatment due to its alkaline properties and porous structure [113,123-124]. Although, it utilized in manufacture of ceramic and glass [124-126], can be reused as crude material in steel plant [125-129] and as potential material in cement production is considered [130-133]. In 2018, nearly 1247 million tone of pig iron were produced in all over the world while typically per each tone of pig iron 350 to 500 kg of slag waste is generated according to recovery recycle technology worldwide [134]. In this study, it was efforted to catch up this opportunity of large amount of slag waste in order to use as cost effective material instead of sand Which is providing from (Kardemir Demir Çelik Fabrikaları A.Ş KARABUK) and produced from steel making slag. Figure 3.8 shows slag waste and placement inside barrier.


(a) (b)

Figure 3.8. (a) Filling slag in the bag, (b) Placement of slag into bag inside barrier.

### 3.5.2. Crumbled Tyre

Tyre is composed of rubber 60% to 65% waste tyres (WT), carbon black (CB) 25% to 35% WT and during manufacturing process the respite which composed of fillers and accelerators are mixed [135]. It is assessed that annually per each person one car tyre is thrown globally and consequently 1 billion of WTs are wasted in all over the world [135]. Pyrolysis1 is utilizing to treat waste tyre disposal and provide high energy and raw material to use in another work. WTs have been used in many civil engineering work due to its cost effective such as partially alternative of aggregate in concrete and mortar [136] or as partially cement alternative in the purpose of improvement of lightweight construction material [137]. Although, WTs have been used in road construction which added to asphalt mixtures and consequently increased skid resistance, decreased maintenance price, increased resistance to rutting, developed tensile strength and increased service life of pavement as compared to simple mixtures [138-139]. Furthermore, rubberized asphalt concrete decreases cost approximately 22000 $ per lane mile over conventional asphalt [136]. In addition, it has been used in geotechnical work as backfill material in retaining wall and as filling material in subgrade road. In this study, it is efforted to utilize this large amount of waste tyre and cost effective as replacement material instead of sand to absorb impact energy. Specific gravity of WTs in this study is (0.6 ton/ $m^3$) with grain size ranging between (0.425 – 4.75 mm) which obtained from (Çetinkaya A.Ş Geri Dönüşüm- Kauçuk Granül/ ANKARA). Figure 3.9 shows the WTs.

Figure 3.9. Waste Tyres.

[1] Pyrolysis separates black carbon from tyre and the volatile matter released.

# PART 4

# THEORY AND METHODOLOGY OF EXPERIMENT

## 4.1. STANDARD FOR ROAD RESTRAINT SYSTEM

In the purpose of developing and sustaining highway safety, the proper design is required to safer road. One of the motives that make the road will be safety is installation road restraint systems (barrier system). These systems are distinguished to redirect errant vehicle safely and avoid from hazard accident. There are many standards according to the countries such as (US, India, Australia, Japan, Korea, European country (EN1317) and etc.). The standards are utilized to identify performance classes which including impact speed of vehicle, impact angle between vehicle and barrier, total mass of vehicle, type of vehicle, level of severity and deflection of the barrier.

In 1962, the first procedure in the name of ‘‘the highway research correlation services circular 482” was published to expose how to crash test for assessing safety hardware is done [140]. In 1993, National Cooperative Highway Research Program (NCHRP Report 350) was considered as the first formal standard, recommended a guideline and evaluation criteria highway features safety which include test parameters, longitudinal barrier, terminal and crash cushions, support structure, work zone traffic control devices, description of test vehicles, data acquisition, implementation and in service evaluation. In 2009, NCHRP report 350 is replaced to Manual for Assessing Safety Hardware (MASH) by American Association of State Highway & Transportation Officials (AASHTO). Among all of test levels (TLs), TL-3 is the most commonly test that use for barrier. So, the mass of car or truck and collision angle are changed from NCHRP 350 TL-3 to MASH TL-3 (changed mass of small car and pickup truck from 820 and 2000 in NCHRP 350 kg to 1100 and 2270 in MASH) respectively, (changed collision angle from 20 degree in NCHRP 350 to 25 degree in MASH) [140]. Also, a difference between MASH and EN 1317 can be appreciate in term of mass and angle (1100 kg car and 2270 kg pickup in MASH, 900 kg and 1500 kg in EN1317) respectively, (25 degree in MASH, 20 degree in EN 1317) [141]. In Korea's standard evaluate the performance of the barrier by index of severity (IS) via conducting full scale crash test. The test conditions consist of (1000 kg) mass of car with (20 degrees) collision angle and (14000, 25000 kg) for trucks with (15 degrees) of collision angle but the impact speed is dividing into five speeds (50, 60, 80, 100, 120 km/h) by depending on the class of the road [142]. In Japanese's standard the performance of the restraint system is conducted according to the type of the barrier. Table 4.1 illustrates the condition of collision vehicle. It can be seen that there are a little differences of test condition between Korea and Japanese standard [71].

Table 4.1. Vehicle impact test of Japanese's standard [71].

| Type of vehicle | Mass of vehicle | Collision angle | Impact speed |
|---|---|---|---|
| Passenger car | 1000 kg | 20 degrees | 60 km/h |
| truck | 25000 kg | 15 degrees | 26 or 30 km/h |

According to the India's standard the crash test of the barrier is classified into three categories as EN1317 [143]. The following Table 4.2 are the specification of collision vehicle.

Table 4.2. Vehicle impact test of India's standard [143].

| category | Weight of vehicle | Collision angle | Impact speed |
|---|---|---|---|
| Normal containment | 15 KN | 20 degrees | 110 Km/h |
| Low containment | 15 KN | 20 degrees | 80 Km/h |
| High containment | 30 KN | 20 degrees | 60 Km/h |

In Australia's standard (AS5100 2004) evaluate the capability of the barrier by classifying into two categories: low performance level and regular performance level.

The low performance criteria specified for light vehicle and low traffic volume but regular levels are for heavy vehicle, cars and specified truck on main roads or highways [144]. Table 4.3 illustrates criteria performance of vehicle.

Table 4.3. Vehicle impact test of Australia's standard [144].

| Level | Mass/type of vehicle | Impact speed (km/h) | Collision angle (degree) |
|---|---|---|---|
| Low | 800 kg small cars<br>2000 kg utility | 70<br>70 | 20<br>25 |
| Regular | 800 kg small cars<br>2000 kg utility<br>8000 kg truck | 100<br>100<br>80 | 20<br>25<br>15 |

**4.2. EN 1317 PERFORMANCE CRITERIA**

EN 1317 is the standard which regulates safety barrier in most country of European such as (British, Germany, French and etc.). It was established in 1998 and in 2010 was revised. This study complies requirements of EN 1317 to perform test method and impact criteria of the road restraint system. This standard defined crash testing procedure, acceptance criteria and level of performance. Although, it does not describe dimension, size, geometry or materials of safety barrier and it also does not distinguish which barrier are to be applied to which road [145]. The impact test acceptance criteria of EN 1317 consists of the barrier should be contain errant vehicle without hurdles longitudinal elements of the road restraint system, no main parts of the safety barrier disported which cause hazard to the pedestrian and people behind the barrier, the centerline of the deformed system should not access by the center of gravity of the vehicle and the vehicle should stay consistently during and after collision. According to EN1317, test method of the safety barrier that should be consider test site and test vehicle. Generally, Test site which includes the surface place of the test should be level and hardened paved, and it should be clear from dust, snow and ice at the time of testing. Also, it should be enough area in order to attain the require velocity, the test vehicle accelerated up and controlled it. Generally, the test vehicle which include the vehicle should be clear from mud and deposits before the test, because it may be induce dust on impact. In order to analyze the test vehicle adequately the marker point should be added on the external surface of the vehicle. While the ballast weight is used for test vehicle, it should not be fixed in location because it would modify the deformation of the vehicle.

In this standard, there are three main criteria of performance which relate to restraint system, include: classes of containment, the impact severity levels, the deformation of the system which include working width and dynamic deflection. Safety barrier should adapt these three criteria during collision in accordance with impact test criteria illustrated in Table 4.4.

Table 4.4. Vehicle impact test description [77].

| Test | Impact speed km/h | Impact angle ° | Total mass kg | Type of vehicle |
|---|---|---|---|---|
| TB 11 | 100 | 20 | 900 | Car |
| TB 21 | 80 | 8 | 1300 | Car |
| TB 22 | 80 | 15 | 1300 | Car |
| TB 31 | 80 | 20 | 1500 | Car |
| TB 32 | 110 | 20 | 1500 | Car |
| TB 41 | 70 | 8 | 10000 | Rigid HGV |
| TB 42 | 70 | 15 | 10000 | Rigid HGV |
| TB 51 | 70 | 20 | 13000 | Bus |
| TB 61 | 80 | 20 | 16000 | Rigid HGV |
| TB 71 | 65 | 20 | 30000 | Rigid HGV |
| TB 81 | 65 | 20 | 38000 | Articulated HGV |

### 4.2.1. Classes of Containment

Defines the capability of barrier to redirect a striking vehicle. This standard identifies four containment levels, which include; low, normal, higher and very high. Table 4.2 identifies the containment level of safety barrier according to the vehicle impact test criteria defined in Table 4.5.

Table 4.5. Containment levels and name of tests [146].

| Containment capacity | Containment levels | Acceptance test |
|---|---|---|
| Low angle containment | T1 | TB21 |
| | T2 | TB22 |
| | T3 | TB41 and TB21 |
| Normal | N1 | TB31 |
| | N2 | TB32 and TB11 |
| Higher | H1 | TB42 and TB11 |
| | H2 | TB51 and TB11 |
| | H3 | TB61 and TB11 |
| Very high | H4a | TB71 and TB11 |
| | H4b | TB81 and TB11 |

Low containment level only tested for temporary safety barrier. While, higher containment level can be used for temporary safety barrier. Also, each prosperity tested barrier at specified level should be regarded as fulfill containment condition of any lower level, except that N1 and N2 do not include T3, H-levels do not include L-levels and H1, H2, H3, H4, H4a and H4b do not include N2.

Hybrid barriers are designed to make harmonization with surrounding area especially in historical, heritage and scenic roads where large vehicles traffic are less and traffic volume with speed are low. EN 1317 standard specified impact test of barrier according to type of vehicle, impact speed/angle [77]. Hence, N1 and TB31 are chosen to conduct pendulum impact test for the barrier.

### 4.2.2. Impact Severity levels

The impact severity of the vehicle occupants is evaluated by acceleration severity index (ASI). The ASI value indicates the dangerous level of the people inside the vehicle during collision with a road restraint system. Table 4.6 defines the impact severity levels of barrier.

Table 4.6. Level of ASI [77].

| Impact severity level | ASI value |
|---|---|
| A | ASI ≤ 1 |
| B | 1.0 < ASI ≤ 1.4 |
| C | 1.4 < ASI ≤ 1.9 |

This table defines that ASI values have classified into three impact severity level A, B, and C. Impact severity A provide safer level of severity of the people inside the vehicle than level B, and level B safer than level A. ASI is a function of time, which is calculated in accordance with the following equation 1.

( Equation 4.1) $$ASI = \sqrt{\left(\frac{\bar{a}_x\,(t)}{\hat{a}_x}\right)^2 + \left(\frac{\bar{a}_x\,(t)}{\hat{a}_y}\right)^2 + \left(\frac{\bar{a}_z\,(t)}{\hat{a}_z}\right)^2}$$

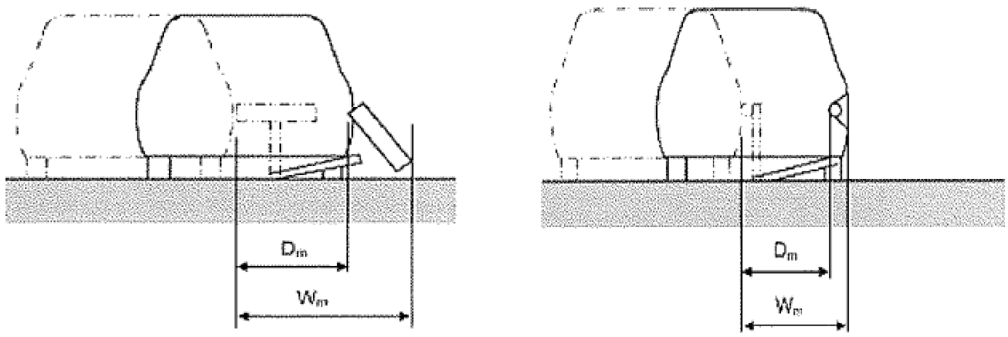
$\hat{a}_x$, $\hat{a}_y$ $and$ $\hat{a}_z$ are the limit value the components of acceleration along the body axes x, y and z.

$\hat{a}_x = 12,\ \ \hat{a}_y = 9,\ \ \hat{a}_z = 10$

$\bar{a}_x\,(t)$, $\bar{a}_x\,(t)$ and $\bar{a}_z\,(t)$ are the components of the acceleration that taken from the test by mounting accelerometer at the center of the gravity of impact vehicle. Because of greater value of ASI means more risk for the occupants, the maximum value of ASI achieved in a collision is considered as a single measure of the severity, or: ASI = max [ASI (t)].

### 4.2.3. Deformation of Restraint System

The deformation of the barrier during collision test is expressed by dynamic deflection and working width. The dynamic deflection is measured as maximum lateral dynamic displacement of any part of traffic face of the barrier. While, working width is measured as maximum lateral distance between any point of the barrier from undeformed traffic side before collision and the maximum dynamic position of any part of the barrier after collision. If the vehicle body penetrates the barrier so that the maximum dynamic position of the barrier cannot be measured in order to compute working width, the maximum lateral position of any point of vehicle should be attained as working width. Figure 4.1 illustrates the dynamic deflection and working width of the (a- barrier) and (b- vehicle).




(a) (b)

Figure 4.1. Working width and dynamic deflection of roadside barrier [77].

The dynamic deflection and working width permit fulfilment of the requirements for installation of each safety barrier and to indicate the area to be available in front of obstacles in the purpose of the system performed satisfactorily. According to the table 4.7 the deformation of restraint system should be classified.

Table 4.7. Working width levels [77].

| Classes of normalized working width levels | Levels of normalized working width (m) |
|---|---|
| W1 | Wn ≤ 0.6 |
| W2 | Wn ≤ 0.8 |
| W3 | Wn ≤ 1.0 |
| W4 | Wn ≤ 1.3 |
| W5 | Wn ≤ 1.7 |
| W6 | Wn ≤ 2.1 |
| W7 | Wn ≤ 2.5 |
| W8 | Wn ≤ 3.5 |

## 4.3. HYBRID BARRIER PENDULUM SYSTEM

In order to obtain license of using road restraint system and perform its labor to provide safety for vehicle occupants, pedestrian and other road user, it should be pass through crash test in accordance with EN1317. Full-scale crash test is one of the crash test method that used to evaluate the performance of road restraint system. Although, full-scale crash test is an expensive test due to constructing of the experiment place (creating an impact path, providing safety wariness, etc.), cost of vehicle with each test and it needs accurately mechanism that assuring the vehicle impact at certain speed and angle. In the literature, pendulum and similar system have been utilized as alternative method of full-scale crash test for the evaluation of barrier performance [147-152]. In addition, it is more economical, practical and suitable in term of safety than full-scale crash test. In 1998, the researchers utilized pendulum system by using 880 kg of pendulum to impact strong steel post W-guardrail as shown in Figure 4.2. The pendulum impacts the post at different velocity, the test was recorded by high speeds camera and measure acceleration by accelerometer. The velocities are 9.25, 20, 30 and 35 km/h, and the result showed that the displacements of the system are 0.15 m at 9.25 km/h after 0.12 s and 0.8 m at 20 km/h after 0.25 s. At 30 km/h, the guardrail can stop the pendulum due to large deflection (1.25 m after 0.22 s), bending and twisting of the post. At 35 km/h of speed, the system could not stop the pendulum safely due to bolt shear failure of the block-out and the test was failed [149].

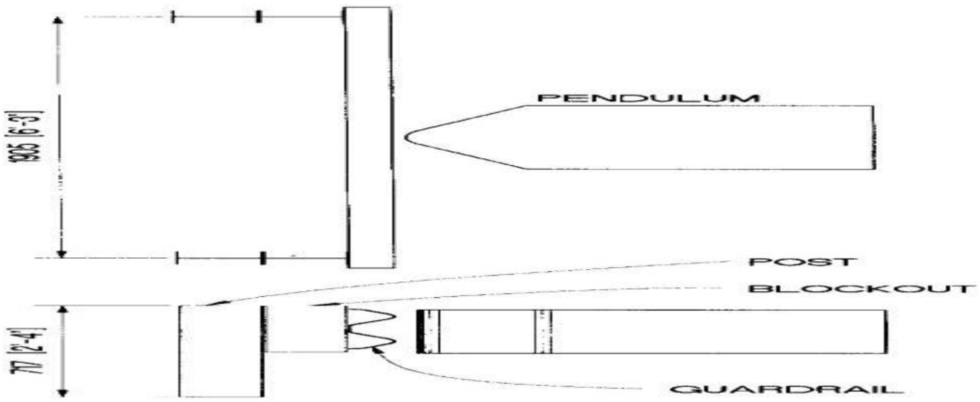



Figure 4.2. Pendulum impact test [149].

In another study, compared two different post embedded depth of strong post round wood barrier (965 and 1118 mm) under dynamic pendulum test as shown in Figure 4.3. The test showed the shorter embedded post (965 mm) dissipate more energy than longer (1118 mm) by means of lateral movement post in soil [53].

Figure 4.3. Dynamic pendulum test on wood post 965 mm [53].

In this study, pendulum system is performed as crash test method which consist of a rigid frame, pendulum rammer is suspended by chains Figure 4.4a. and electric chain pulley Figure 4.4b, the pendulum rammer is lifted. The pendulum rammer was uplifted by electric chain pulley to desired height to achieve the required initial impact velocity and then letting the pendulum rammer back down for free fall as shown in Figure 4.5. Although, the chain was positioned such that the pendulum rammer hit the target point of barrier. By this way, it can be obtained the same energy to impact barrier at the same speed each time.

(a)

(b)

Figure 4.4. (a) Pendulum rammer and (b) Electric chain pulley

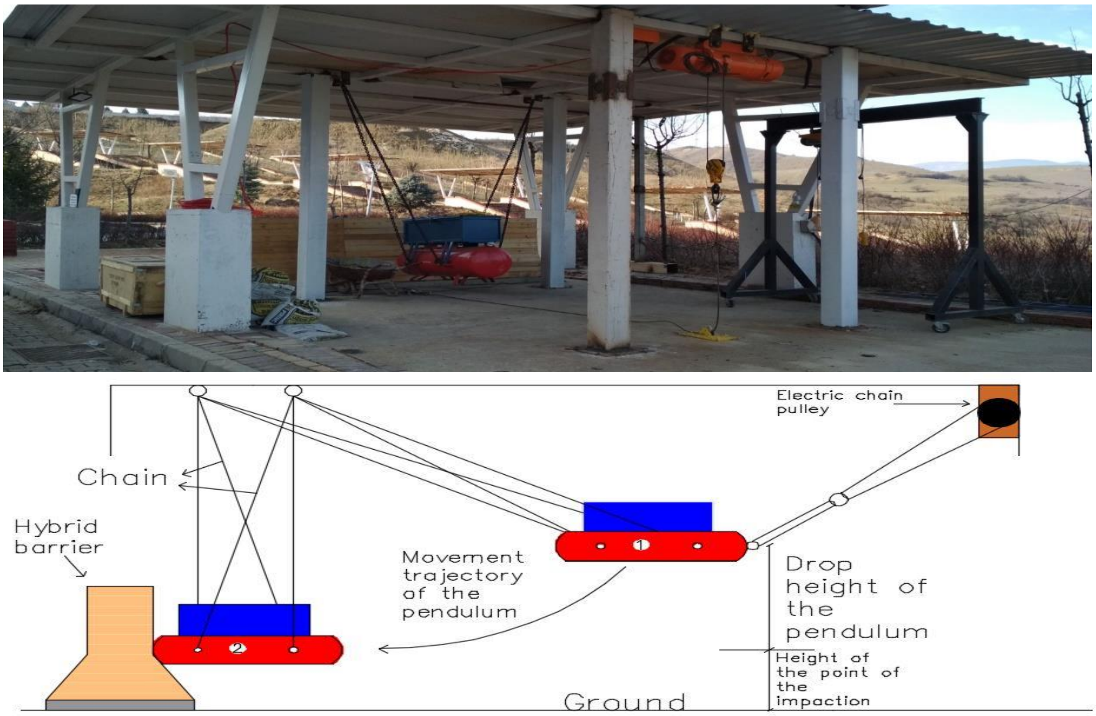



Figure 4.5. Pendulum system crash test of hybrid barrier

The pendulum rammer consists of a cover of 10 mm thick steel sheet and filled with ballast weight of iron powder to obtain the required mass which equal to 1500 kg in order to fulfil requirement of TB31 vehicle mass. Four rods of chains were used to suspend the pendulum rammer by each two chains on each side in order to obtain the balance of vehicle during impaction and avoid from lateral oscillations.

The pendulum system provides amount of potential energy when it is raised to desired height number 1 position in Figure 4.5. According to the potential energy equation.

(Equation 2) $Ep = m*g*h$

Whereas: EP is total potential energy (J), m is mass of pendulum rammer (kg), g is gravitational acceleration ($m/s^2$) and h is the desired height of the pendulum rammer (m).

According to the law of conservation of energy, when the pendulum rammer is lifted to required height, it possesses desired potential energy. When the pendulum rammer is released, it becomes downward under gravitational force and potential energy transformed to kinetic energy, which is exerted by moving object. It is mean that when it is raising the potential energy increases until that moment the pendulum rammer was stopping, then it falls down and converts to the kinetic energy which is increasing until the lowest point before the moment of collision with target point of barrier and the kinetic energy becomes zero when the barrier reaches the maximum displacement. In this study, the desired height is number 1 position which has potential energy equal to the desired kinetic energy in the number 2 position. According to the containment level and crash test Figure 4.6 indicates amount of energy generated on the barrier. In this study, normal containment level (N1) is applied on the barrier which means 43 kJ energy is generated. According to the formula, it was determined that the desired height of the pendulum rammer should be equal to 2.93 m to obtain 43 kJ of energy.

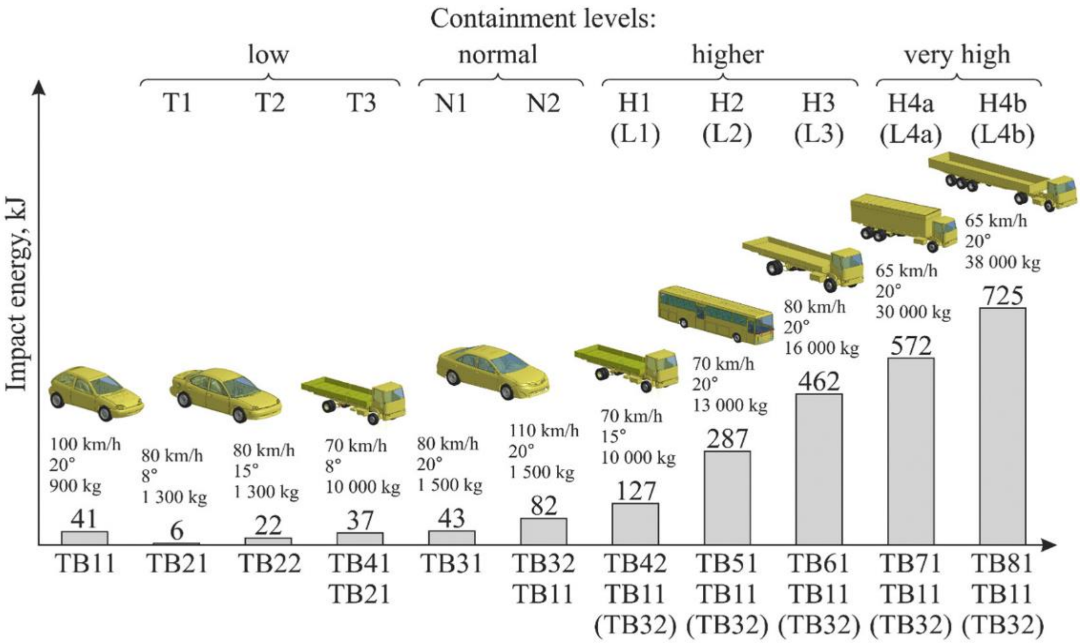



Figure 4.6. Classification of containment level by dependent of vehicle type [77].

In this study, the acceptance test TB31 is planned to be applied in order to impact an energy of 43 kJ during releasing the pendulum. Figure 4.7. Shows the crash test of TB31, which 1500 kg mass of vehicle impact the barrier at 80 km/h and 20 degrees of collision angle. When the vehicle impacts the barrier, F is divided into two components Fx and Fy. The Fy component represents the falling force on the barrier during collision.

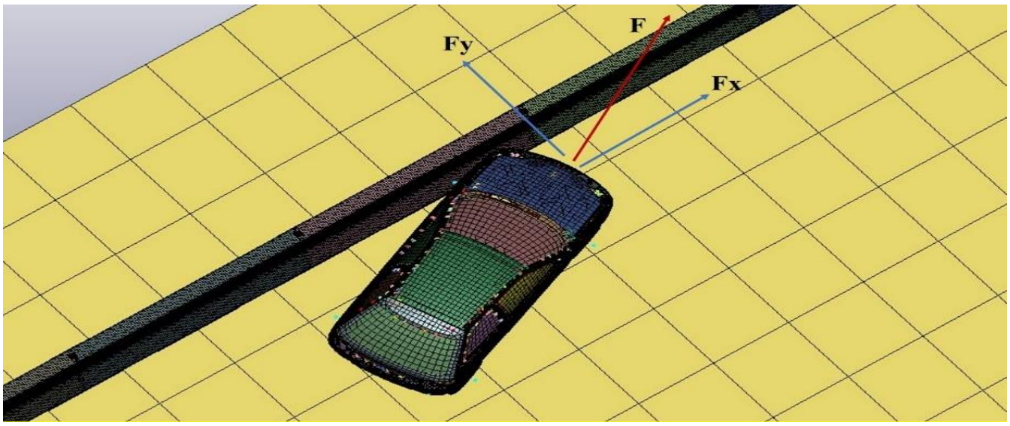



Figure 4.7. Components of impact force [153]

The total energy is generated in the Fy direction (component falling in the barrier) should be equal to 43 KJ, according to the equation 3.

( Equation 3 ) $$E = \frac{1}{2} \times m \times \left(\frac{V}{3,6}\ x\ sin\, 20\right)^2$$

E : energy of Fy direction (J)

m : mass of vehicle (kg)

v : vehicle speed (km/h)

Briefly, according to the EN 1317 standard, the hybrid barrier system is applied TB31 vehicle impact test and (N1) normal containment level test criteria which the test is 1500 kg of pendulum rammer is uplifted by electric chain pulley mounted on pendulum system frame until achieve 2.93 m of pendulum rammer or 1.73 m of its center of gravity which is measured by surveying instruments. Each test is carried out with the same procedure and energy of 25.5 KJ was applied on the barrier each time. EN 1317 standard is not described the difference height between level ground and the impact point of the pendulum rammer. Although, in the light of the literature the difference height is assessed equal to 50 cm and then the rammer was hung on the pendulum system frame.

## 4.4. FINITE ELEMENT ANALYSIS

Finite element analysis (FEA) consists of using FE models to describe vehicles and barrier in impact simulation. Simulations analyze the physics of the diverse part of the models for tiny time interval (micro seconds) during the period of collision incident (vehicle impacting the barrier). Because, there is a contact between the elements of barrier and vehicle which consequently the barrier will deform, displace or fail due to the applied force of vehicle according to the behavior of materials and connection between elements (joints and fracture mechanism). There are many studies that based on FE models initiate innovative design and performance evaluation [154-155]. In the literature review, LS-DYNA and other simulation like ABAQUS, MADYMO, MEPHISTO, etc. have been successfully used to evaluate safety barrier performance [156-159] . In the purpose of using as alternative method instead of experiment crash test to save time and decrease cost of crash test because of evaluation of all tests with many conditions are costly, difficult and needs the time [155]. In some cases, the finite element models are compared with full scale crash test, it shows that the simulations are similar and correlated well with experiment work [140]  as shown in Figure 4.8.

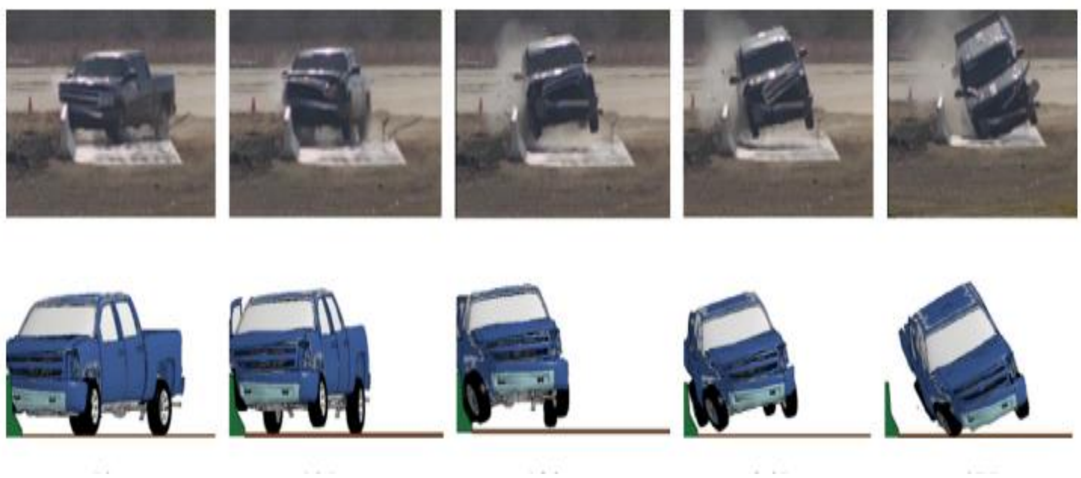


Figure 4.8. Comparison between full scale crash test and simulation [140].

In this study only experimental results were obtained. The experimental results will be a basis for the validation of FEM simulations and by this way virtual full-scale tests will be carried out for future studies.

### 4.5. DATA PROCUREMENT

In order to evaluate crash performance of the hybrid barriers in accordance with EN 1317, the ASI and working width (W) as illustrated above from equations and table should be calculated. For this purpose, two cameras were fixed as shown in Figure 7.9 which the standard is indicated their place so that one was recording from the side view (Casio Exilim Pro EX-F1) and the other was recording from the top view (GoPro Hero 5). Although, accelerometer device (PCB Piezotronics-350A43) as shown in Figure 4.10 was mounted at the centre of gravity on the pendulum rammer. In addition, to demonstrate the observes that obtained from the cameras 7.5 cm diameter as vector illustrator was pointed at specify location of pendulum rammer as shown in Figure 4.11. Furthermore, a yellow line was drawn on the ground to fix the starting point of each experiment as shown in Figure 4.12. By "ImageJ" program working width is also measured which camera videos recorded as shown in Figure 4.13.


Figure 4.9. Cameras of the test

Figure 4.10. Accelerometer device

Figure 4.11. Vector illustrator

Figure 4.12. Yellow line

Figure 4.13. imaging process of the test

### 4.6. EXPERIMENTAL MATRIX

It was guessed that with the constancy of wood parts, concrete base segments and steel elements, the changing of filling materials such as slag and tyre plastic instead of sand would have an influence on the crash performance of the hybrid barrier. Thus, the experiment matrix was formed as shown in table 4.8. A total of seven hybrid barriers were generated by using different filling material which include; three of tests were sand, two of them were slag and the last two tests were tyre.

Table 4.8. Properties of hybrid barrier

| Filling material | Name of test | Specific gravity | Thickness and type of wood | Particle size of material | Applied energy |
|---|---|---|---|---|---|
| **Sand** | **B1T1** | **1,60 ton/m$^3$** | **4 cm** | **0.425 – 4.75 mm** | **25 kJ** |
| **Steel making Slag** | **B2T1** | **2,08 ton/m$^3$** | **4 cm** | **0.425 – 4.75 mm** | **25 kJ** |
| **Crumbled Tyre** | **B3T1** | **0,60 ton/m$^3$** | **4 cm** | **0.425 – 4.75 mm** | **25 kJ** |

# PART 5

# RESULTS

All the hybrid barriers were tested by the pendulum crash system through striking the middle point. According to the table 4.8 all the testes were carried out. Figure 5.1 illustrates the front side and back side shape of the barrier test after pendulum impacting, and the data observations of (W) and (ASI) were obtained crash test are presented in Table 5.1 and 5.2.

**Front side** **Back side**

**B1T1** **B1T1**

**B2T2** **B2T2**

**B3T1** **B3T1**

Figure 5.1. Deformation shape of the barriers after pendulum impacting

Generally, in sand and slag tests of the barrier the deformation shape of segments of the timbers were similar but the tyre test is different. In sand and slag, nearly four to five segments of timber were broken or bended after pendulum impacting, at the same time there is no deformation occurred in the backside of the all tests of hybrid barrier. This may assign that the kinetic energy of the pendulum is absorbed satisfactorily by sand or slag with timber, but the tyre is entirely different from sand and slag.

Table 5.1. Value and class of working width of the hybrid barrier

| **Filling material** | **Name of test** | **Working width (m)** | | **Class of working width** |
|---|---|---|---|---|
| | | **25.5 kJ** | **43 kJ** | **43 kJ** |
| **Sand** | **B1T1** | **1.085** | **1.83** | **W6** |
| **Slag** | **B2T1** | **1.197** | **2.02** | **W6** |
| **Tyre** | **B3T1** | **1.535** | **2.59** | **W8** |

Table 5.1 illustrates the working width levels indicated considering the test result. In consequence of the light of observations of the pendulum crash test which obtained from camera images, it is indicated that the working width of the hybrid barriers ranged between (W6 - W8) for different types of filling material.

By depending on the result of the tests, there is no perspective difference between B1T1 and B2T1 in the term of working width distances and classes. The studies in the literatures, it is indicated that both of sand and slag can be utilized due to its potential energy [160-163]. In accordance with the literature, it has utilized slag and sand in hybrid barrier in order to improve working width. Although, the studies indicated that there is no explicit affect between 20 mm and 40 mm thickness of the timber in term of working width. Also, the result indicated that tyre as comparing with slag and sand, it has a large working width and its potential value less than sand and slag. From this view, the results indicate that sand is better than slag and slag is better than tyre in term of decrease working width. Although, all tests of sand, slag and tyre as filling material within limit of acceptance criteria in term of working width according to the EN 1317.

Other factor that should be consider in testing road restrain system is ASI. In this study, in order to ensure safety of hybrid barrier ASI is measured for all tests as shown in Table 5.2.

Table 5.2. Value and class of ASI of the hybrid barrier.

| **Filling material** | **Name of test** | **Deceleration of 25.5 kJ ($m/s^2$)** | **ASI value of 25.5 kJ** | **Deceleration of 43 kJ ($m/s^2$)** | **ASI value of 43 kJ** | **ASI class of 43 kJ** |
|---|---|---|---|---|---|---|
| **Sand** | **B1T1** | **5.36** | **0.45** | **9.04** | **0.75** | **A** |
| **Slag** | **B2T1** | **5.47** | **0.46** | **9.24** | **0.77** | **A** |
| **Tyre** | **B3T1** | **15.05** | **1.25** | **25.38** | **2.11** | **Null** |

Table 5.2 shows the deceleration value of the 25.5 KJ which is obtained from experiment test by mounted accelerometer on the pendulum rammer and was

converted to ASI of 25 kJ by (eq.1). After that, two values of deceleration 25 kJ and ASI of 25 kJ was converted to deceleration of 43 kJ and ASI of 43 kJ in order to fulfil requirement of TB31 crash test in accordance to EN 1317. The table appears that the ASI value of sand and slag approximately are equal to each other which are classified to A class while the ASI value of tyre is so far from sand and slag which cannot be classified to ASI class due to its value (2.11) was not within limit of acceptance criteria in term of ASI according to the EN 1317 because maximum value of ASI equal to (1.9). Generally, sand and slag have same ASI with same safety condition. But the tyre has larger value than slag and tyre and also it is not in safety condition. Consequently, both ASI values of sand and slag which obtained from crash tests are acceptable and tyre is unacceptable within limits classes of ASI in accordance to EN 1317. Eventually, the result indicate that the hybrid barrier will keep the occupant vehicle at the required limit during an impact with sand and slag but with tyre is not suitable.

## PART 6

## DISCUSSION

From the result of the test, it can be obtained that using sand and slag as filling material of hybrid barrier can satisfy requirements of a safety barrier and contain errant vehicle through energy absorption via lateral deflection. Although, when using tyre as filling material of hybrid barrier satisfy working width condition of the test but failed to pass condition of ASI test criteria. When the hybrid barrier is tested (TB31), the vehicle would not penetrate and underride or override the hybrid barrier.

The design and energy absorption of the hybrid barrier can be considered as a suitable alternative of steel guardrail and concrete barrier. Because of steel guardrail due to its sharp edges/ terminal points and concrete barrier due to its rigidity have a big risk in the life of occupants especially crashing motorcycle with steel guardrail.

The shape and flowers of hybrid barrier makes a harmonization with surrounding area especially with historical, mountain, touristic, natural rural and heritage zones. The future studies can improve its shape according to its purpose. The flowers on the upper part of the hybrid barrier reduce the effect of headlight from opposite traffic lane at night which decrease crash accident consequently.

In the literature, one of the main disadvantages of using wooden barrier is the cost. So, in this study it is tried to use wood barrier with minimum cost which by using filling material like sand and slag in the hybrid barrier that reduce the cost convincingly.

There are a few limit numbers of wooden segment deformation after impacting pendulum crash test. However, slag/sand and tyre of the hybrid barrier due to their natural composition did not deform. This is the main reason of low maintenance, repair rapidly on site after impaction and low cost. It is attributed that hybrid barrier play a role in in the reduction of air pollution/waste production, improvement of natural resource by recycling process through using waste material and natural material like timber.

It is recommended to concern more studies in this subject to expand the range of using natural / waste material and wood segment that are suitable for recycling process and cost reduction. This research can consider as the first point or basis for next step, real time crash test.

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# RESUME

Zagros Othman Ali completed his primary and secondary education in this city. After completing his high school education in Shorijah in the same city, he started his undergraduate program at Kirkuk university civil engineering department in 2014. After graduating from the department of civil engineering in 2018, he started to work as a civil engineer in a company and as a effectuate and supervision engineer in 2018. In 2019, he started his master thesis at Karabuk university institute of graduate programs, department of civil engineering.