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A Comprehensive Review of Seismic Performance Enhancement in Steel Plate Shear Walls using Waste Tyre Rubber Aggregates: Materials, Methods, and Structural Behavior

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Abstract*: The authors present an overview of significant developments in seismic-resistant building using a combination of waste tyre rubber aggregates integrated into concrete and steel reinforced plate systems. Recent concerns regarding seismic vulnerability globally and environmental sustainability have resulted in a surge of interest in new composite materials for enhancing both structural durability and waste recycling. In addition to discussing experimental data and comparisons of mechanical properties, seismic behavior and energy absorption capacity of shear walls constructed with rubberized concrete and reinforced steel plates, this literature review also includes discussions of application of these composite materials, construction techniques and possible regulatory pathways for implementation. Based on the results of experimental studies and comparison of data, the review identifies that hybrid composite systems of steel-reinforced rubber concrete may be a viable method of providing resilient and environmentally sustainable structures, specifically when rubber is replaced at levels of approximately 10-15% by volume of coarse aggregate*

Keywords: Seismic-resistant construction**,** Waste tyre rubber, Steel plate reinforcement, Energy dissipation

I. INTRODUCTION

With an increasing concentration of urban populations in highly seismic areas, Earthquake Resistant Design (ERD) is now considered one of the greatest challenges to civil engineers in the 21st Century. While traditional Reinforced Concrete (RC) structures are generally effective under static loads they often fail in a brittle manner when subjected to the cyclically varying lateral forces associated with seismic events [1]. In addition, the rapid growth in the number of End Of Life Tyres (EOLT) represents a major environmental problem. Millions of tons of EOLT are disposed of each year, creating serious disposal problems and hazardous environments [2]. The combination of ERD and the growing problem of EOLT has led researchers to investigate if the use of Waste Tyre Rubber (WTR) could be used to improve the seismic performance of structural concrete whilst at the same time providing an environmentally friendly solution. Experimental studies have shown that partial replacement of natural coarse aggregate by processed WTR particles can result in significant changes in the mechanical and dynamic properties of the concrete [3]. These modified concrete mixes when combined with Steel Plate Reinforcement Systems (SPRS) offer the possibility of developing Hybrid Shear Wall (HSW) assemblies which possess enhanced ability to dissipate seismic energy, greater ductility and improved cracking resistance than conventional RC shear walls [4]. The elastic characteristics of WTR particles introduce internal damping mechanisms which assist in absorbing seismic energy, while SPRS provide the required tensile strength and load redistribution capabilities [5].

The primary purpose of this review paper is to draw together existing knowledge relating to the seismic behaviour of Steel Plate Shear Walls (SPSW) constructed using WTR as an aggregate, focusing on material characterisation, experimental methods employed, performance measures and practical issues related to their implementation. It aims to provide researchers, practising engineers and policy makers with a detailed understanding of this novel structural approach and its potential to be applied extensively in earthquake prone regions.

II. MATERIALS CHARACTERIZATION AND MIX DESIGN

2.1 Waste Tyre Rubber as Aggregate

Rubber tire waste material has unique physical and mechanical properties relative to the aggregate used in concrete construction as well as other aggregates. The particle densities for rubber waste are generally reported to range from 1,000 to 1,200 kilograms/m³ (approximately 1/2 to 5/8 of the 2,600+ kg/m³ typical of most natural coarse aggregates) [6]. The lower particle density of rubber results in an overall lighter weight (lower "dead" loads) for the resulting lightweight concrete that may provide advantages for seismic design since less structural mass results in lower inertial forces due to ground motion [7].Rubber is also significantly more flexible than conventional stone aggregates, contributing to added flexibility to the concrete matrix. The ability of rubber to deform under applied stresses, followed by some degree of recovery of its original form upon removal of the applied stress, provides a damping action that increases the ability of the concrete to absorb energy [8]. However, this same property of rubber also contributes to the decrease in compressive strength that occurs with high enough levels of rubber content in the concrete. Studies indicate that there is a ten to twenty-five percent loss in compressive strength as the percentage of rubber content increases up to fifteen to twenty percent by volume [9] [10].The transition zone between the rubber particles and the surrounding cement paste is an important factor in designing mixes. The rubber particles have hydrophobic surfaces and smooth textures, both of which result in poor bonding characteristics between the rubber particles and the surrounding cement paste [11]. Several methods have been proposed to improve these bonding characteristics, such as washing the rubber particles with sodium hydroxide, applying silane coatings or partial oxidation, each designed to increase the surface roughness and compatibility with the cement paste [12] [13].

2.2 Steel Plate Reinforcement

Steel plates provide a high degree of tensile strength and flexibility when used in hybrid shear walls to support and reinforce the concrete. These plates are provided with either an embedment through the exterior face of the wall or externally attached to the wall to enhance tensile resistance and to redistribute tensile stresses throughout the wall. Commonly, the plates have a thickness range of three to ten mm; yield strength of approximately 250 MPa; and an ultimate tensile strength of about 410 MPa [14]. The addition of steel plates changes the failure mechanism of shear walls from a brittle diagonal tension failure to a more ductile flexural-yielding failure mechanism [15]. Proper interface preparation is necessary for the composite action (i.e., interaction) of the steel plates and concrete. The research shows that welded dowel, mechanical bolt, and epoxy adhesive connections will efficiently transfer load from the steel to the concrete at the interface; however, the type of connection used affects the initial stiffness of the connection and post-yield behavior of the connection [16]. Steel plates function as crack arrestors by spreading tensile forces over a larger area than if the forces were being transferred along the length of individual cracks, which helps prevent the coalescence of multiple cracks into a single plane of failure [17].

2.3 Optimal Mix Proportions

Optimizing Rubber Content as it relates to other Performance Criteria for Concrete is a function of achieving an appropriate balance of these criteria. Studies using experimental methods have shown that replacement levels for rubber (5-15% by Volume of Coarse Aggregate) can be used to obtain satisfactory balances of Strength Retention and Enhanced Seismic Characteristics [18] [19]. At ten percent replacement, Compressive Strengths of eighteen to twenty-two Mega-Pascals have been measured in laboratory tests after twenty-eight days of Standard Curing on mixes designed for structural applications in low to mid-rise buildings [20]. The modification of Design Procedures for use in mix designs has followed standard practices with consideration of the Lower Specific Gravity of Rubber and Altered

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Workability Characteristics of Rubber when compared to conventional aggregate systems. Frequently, Super-plasticizers have been added to mixes at dosages of 0.8% to 1.2% by Weight of Cement to Maintain Acceptable Slump Values of seventy-five to one hundred Millimeters [21]. The Water-Cement Ratios have been Maintained Near 0.45 to Ensure Adequate Hydration for Concrete Systems While Accommodating the Non-Absorbent Nature of Rubber Particles [22].

III. EXPERIMENTAL METHODOLOGIES

3.1 Specimen Preparation and Testing Protocols

The sizes of hybrid shear walls tested in accordance with standard test procedures are generally on the order of a 1,000 mm (approximately) tall by 600 mm wide by 100 mm thick specimen [23] to preserve favorable aspect ratio for combined flexure/shear response to lateral loads; as well as being feasible for a typical laboratory testing facility [24]. Standardized reinforcement details were based upon existing code provisions that address the use of seismic design codes' detailing requirements for boundary elements (confinement), the minimum amount of reinforcement, and the requirement to detail the system to be ductile [25], [26]. The vertical reinforcement is generally provided with 12 mm diameter reinforcing bar at 150 mm center-to-center spacings; horizontal reinforcement is provided with 8 mm diameter bars at 200 mm center-to-center spacings [27]; steel plate reinforcement may be placed either centrally within the wall's thickness or mechanically attached to the outside surface of the wall via fasteners and adhesive [28].

3.2 Loading Protocols and Instrumentation

The quasi-static cyclic loading test is the most common experimental procedure used to evaluate the seismic behavior of a structure. The quasi-static cyclic loading test uses a displacement controlled protocol that applies an incremental increase in lateral displacement in both positive (push) and negative (pull) directions. These increases simulate the bidirectional cyclic nature of the reverse motion found in earthquake ground motion [29]. A typical loading sequence begins with small amplitude cycles (either +2mm or -2mm), then progresses through cycles of +5mm, +10mm, +15mm, +20mm, or continues until there is a significant loss of strength [30]. All of these parameters are measured using comprehensive instrumented arrays which measure the structural response parameters including load-displacement relationship, strain distribution, and crack development. Linear Variable Differential Transformers (LVDT's) are located at multiple heights on the specimen and measure lateral displacements to an accuracy of ±0.001 mm [31]. Strain Gauges are attached to the reinforcement bars and steel plates to measure localized deformation and identify yielding areas [32]. Digital cameras and Crack Width Comparators are also used to record crack development and failure mechanisms [33]. Dynamic response information can be obtained via shake table testing using simulated earthquake acceleration records. Specimens are tested under scaled versions of recorded earthquakes (e.g., El Centro or Bhuj earthquake) with maximum ground accelerations of between 0.2g and 0.6g [34]. Accelerometers are used to measure transmitted accelerations and amplification factors, whereas non-contact displacement sensors measure real-time lateral movement [35].

IV. MECHANICAL PROPERTIES AND PERFORMANCE CHARACTERISTICS

4.1 Compressive Strength and Density

The substitution of waste tire rubber (as coarse aggregate) always results in a corresponding reduction in compressive strength to the extent of the percentage of substitution. The substitution of five percent of rubber into the mix results in an approximate decrease of 8 – 12 percent of the compressive strength at 28 days; ten percent will result in a 15 – 20 percent decrease [36] [37]. More than twenty percent substitution of rubber results in greater decreases in strength, often in excess of 30 percent [38], resulting in concerns regarding structural integrity.

Although rubberized concrete exhibits decreased compressive strength compared to conventional concrete, it also displays new modes of failure which could be beneficial during seismic events. The failure of conventional concrete occurs catastrophically (i.e., rapidly), in a brittle fashion when maximum stress is reached, whereas the failure of rubberized concrete involves a more gradual post-maximum stress softening with increased strain capacity [39]. The increased deformation capacity of rubberized concrete provides evidence of impending failure, allowing structural components to undergo large displacement prior to complete loss of load carrying capacity [40].

Density reductions associated with the addition of rubber to the mix are estimated to range between 5 – 15 percent dependent upon the amount of rubber substituted into the mix; approximately 21 hundred kg/m3 is estimated to represent a density value for ten percent rubber content, as opposed to 24 hundred kg/m3 for conventional concrete [41]. Although this represents a decrease in mass, this reduction in mass is likely to produce a decrease in the seismic inertial force which would potentially counteract some of the deficiency in compressive strength through decreased demand instead of increased capacity [42].

4.2 Ductility and Energy Dissipation

The rubberized material exhibits a notable improvement in ductility compared to non-rubberized, conventional concrete subjected to earthquake forces; thus, the ductility factor (ultimate displacement/yield displacement) is increased from 2.5 for the non-rubberized mixture to 4.5–6.5 for the best-performing, rubberized mixtures [43] [44]; this enhanced ductility allows rubber particles to bridge microcrack openings and provide stress redistribution, thereby providing additional time to develop the critical failure surfaces [45].

Energy dissipation capabilities are also improved by the incorporation of rubber into the matrix. Hysteretic loop analysis has shown that the amount of energy absorbed during cyclic loading is significantly increased in specimens that contain ten to fifteen percent rubber when compared to the energy absorbed by the specimens that did not have rubber in the matrix [46] [47], due to an increase in the area enclosed within the hysteretic loops of the specimens that contained rubber. Additionally, wider hysteretic loops with less pinching were obtained with rubber-containing specimens, indicating that these specimens can absorb energy internally through frictional resistance and elastic deformation [48].

Incorporating both rubber aggregate and steel plate reinforcement into the hybrid specimens produces an additive effect on improving ductility and energy absorption. In fact, hybrid specimens exhibit ductility factors greater than 7.0 and demonstrate a cumulative energy absorption capability greater than 300% of that exhibited by conventionally reinforced concrete wall specimens [49]. The mechanism for achieving superior performance in hybrid specimens involves complementary action of rubber (which enhances internal damping and flexibility) and steel plates (which provide lateral confining pressure and plastic deformation capacity) [50].

4.3 Crack Resistance and Failure Modes

Crack growth behavior in response to cyclic lateral load varies greatly among traditional and rubberized concrete. The initial cracks in traditional concrete occur relatively early in a cycle and rapidly grow into several major diagonal cracks that radiate from the lower corner of each panel towards the middle height of the wall [51]. These large cracks continue to grow wider during subsequent cycles until they cause failure through crushing of the concrete at the compressive toe and failure of the reinforcing bars due to bar buckling [52].

In contrast to traditional concrete, the cracks in rubberized concrete are initiated much later during the first few cycles, and instead of having a few major cracks the rubberized concrete has many smaller cracks [53]. Rubber particles function as crack bridging agents. As the cracks develop in the rubberized concrete the rubber particles absorb the deformation in the vicinity of the developing crack, thus inhibiting the cracks from growing together and becoming the primary failure surface [54]. In addition, the width of these cracks is typically less in rubberized concrete, and the rate of growth of cracks in rubberized concrete is generally less than for traditional concrete [55].

The use of steel plates to reinforce rubberized concrete panels provides additional crack controlling benefits by allowing the steel to restrain the development of tension stresses and redistribute them away from the cracks [56]. In reinforced panels, cracks tend to occur outside of the zones of the steel plates and are narrower than those in unreinforced panels due to the confinement provided by the steel plates [56]. This results in a transition from the typical brittle shear-dominated failure mechanism of traditional concrete to more ductile flexural yielding-type failure mechanisms where the damage develops progressively and not catastrophically [57][58].

4.4 Stiffness Degradation

The low elastic modulus of rubber particles makes rubberized concrete walls inherently less stiff in the beginning than traditional walls; however, they have a more favorable rate of loss of stiffness during cyclic loads. Rubberized concrete retains a larger portion of its original stiffness throughout an extended series of cyclic loads than does traditional concrete as soon as it has developed cracks significantly (i.e., approximately fifty percent of original stiffness is lost by traditional concrete after only five cycles of loading), while rubberized concrete retains greater portions of its original stiffness throughout longer series of cycles (i.e., after ten cycles, reinforced rubberized concrete retain over sixty percent of original stiffness, as opposed to approximately forty percent retained by un-reinforced walls) [59-61]. Steel plate reinforcement greatly enhances the initial stiffness and stiffness retention characteristics of rubberized concrete. Specimens with steel plate reinforcement retain greater than sixty percent of their original stiffness after ten loading cycles as opposed to about forty percent of original stiffness retained by unreinforced walls [59]. The composite action between the steel plate and the concrete wall prevents the extreme opening of cracks in the wall caused by cyclic loading and creates alternative load paths that allow for continued lateral resistance of the wall even as additional damage accumulates [59]. Systems that combine rubber aggregate with steel plate provide the greatest amount of stability in terms of stiffness characteristics. These hybrid systems are able to retain nearly seventy percent of their original stiffness throughout the entire history of displacements [63]. This increased resilience of these hybrid systems is a result of a combination of the internal frictional or viscous forces provided by the rubber aggregate and the external constraints or restraints provided by the steel plate. As such, these hybrid systems are able to create a balanced system that resists rapidly deteriorating, especially when subjected to large amplitude displacement histories [63].

V. SEISMIC BEHAVIOR AND PERFORMANCE ASSESSMENT

Figure 1. Seismic Performance Assessment. (Source: Original Image)

5.1 Load-Displacement Response

The way that reinforced concrete walls deform under load is a good indicator of their seismic performance. The amount of strength the walls can develop, the amount of deformation they will allow before failing and how much they will continue to carry a load after they have reached maximum strength are all important aspects of seismic performance. Conventional reinforced concrete walls are characterized by a rapid increase in load on the wall immediately after the wall begins to deform (a "steep" slope) followed by a sudden loss of strength once the peak load has been reached; the loss of strength occurs abruptly. These walls are classified as "brittle", and thus do not possess the properties that would make them suitable for seismic applications. Peak lateral loads for these types of walls occur at very small displacement levels, generally less than a one percent drift ratio, and conventional walls do not retain any significant residual strength beyond this displacement level. Walls made from rubberized concrete exhibit a significantly more gradual load-deformation curve, and maintain a larger load-carrying capacity at large deformation levels than conventional walls. The maximum loads developed by rubberized concrete walls are typically 10-20% lower than those developed by conventional walls because of the reduced compressive strength of the rubberized concrete; however, the rubberized concrete walls sustain a significant portion of the maximum load at large deformation levels, and well into drift ratios greater than 3%, which is far beyond the point that conventional walls have lost all of their strength. Adding steel plates to rubberized walls produces a hybrid wall that possesses both sufficient strength and significant deformation capacity, providing a unique seismic response profile that is consistent with the requirements of performance-based design objectives. The hybrid walls produce peak loads similar to or greater than conventional walls, but provide a load-carrying capacity over drift ratios of 4-5%.

5.2 Hysteretic Behavior and Damping

Characteristics of hysteresis loops, in addition to providing significant information regarding the mechanism for dissipating energy and the degree of stability of structures subjected to cyclic reversed loads, are also very informative as to how well energy is absorbed by structures during cyclic reversed loading. Hysteresis loops produced by conventional concrete walls have typically been observed to be narrow and "pinched," which results from the degradation of the bond between the wall and its reinforcement, crack closure and reopening (i.e., the cracking process), and limited plastic strain [71]. As stated above, "pinching" of the hysteresis loop indicates a low level of energy dissipation and a greater propensity for the structure to behave as if it were stiffness dominated as opposed to being strength dominated [72]. Hysteresis loops generated by rubberized concrete have been found to be much broader, having a rounded shape and minimal pinching, indicating that rubberized concrete has good, stable energy absorbing properties due to material damping [73]. In addition to the broadening of the hysteresis loop, the elastic recovery of rubber particles after the load has been removed results in a fuller hysteresis loop and lower residual displacements when compared to those of conventional concrete [74]. These characteristics indicate that hybrid walls will have damping ratios that will range from five to seven percent of the critical damping ratio, which is significantly larger than the two to three percent damping ratio of conventional concrete [75]. The addition of steel plate reinforcement provides an additional source of energy dissipation in the form of yield of the steel plates under tension. The combined energy dissipation provided by both the material damping of the rubber and the hysteretic damping provided by the yield of the steel plates provides a dual-mechanism system with a high ability to absorb large amounts of energy [76]. Amongst the various configurations tested, hybrid walls have been shown to produce the largest, most stable hysteresis loops, with the amount of cumulative energy dissipated by these walls being equal to or greater than the design basis seismic demand [77].

5.3 Residual Displacement and Self-Centering

The degree of residual displacement (drift) after an earthquake will determine if buildings can be restored to full function and alignment, or if they need to be demolished and rebuilt. Typical concrete walls in earthquakes show a lot of residual drifts because of the permanent crack openings that occur during the event, the yielding of reinforcing steel, and the crushing of the concrete [78]. These permanent deformation issues create serious problems with building serviceability and add complexity to post-earthquake repairs [79]. Rubberized concrete exhibits a better self-centering capacity when subjected to earthquake loads than conventional concrete walls do; this is primarily attributed to the elastic recovery of the rubber particles embedded within the rubberized concrete. After the load is removed from a rubberized specimen it tends to return closer to its original position than a conventional wall, with the residual drift being about 30% to 50% less than those exhibited by conventional walls [80]. Rubberized concrete's properties are especially important to essential facilities (hospitals, emergency operations centers, etc.) where continuing operation after an earthquake is mandated [81]. The restrained restoring force provided by steel plate systems also contributes to lower residual displacements than conventional walls. When combining the elastic recovery of rubber particles and restraining force of steel plates, a hybrid wall is formed which has almost no residual drift, often less than 0.5% [82] at peak drift values greater than 3%. This self-centering capability provides a considerable benefit for seismic resilience and post-earthquake functionality [83].

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VI. ENVIRONMENTAL AND ECONOMIC CONSIDERATIONS

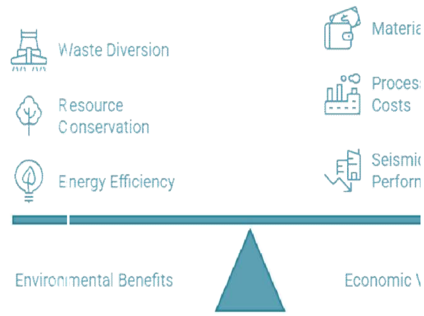

Figure 2. Balancing Environmental and Economic Benefits of Rubber-Steel Hybrid Walls. (Source: Original Image)

6.1 Sustainability Benefits

Using waste tyre rubber as a component of structural concrete provides an environmentally beneficial solution to issues associated with the disposal of used tyres. The world produces approximately one billion tyres at end-of-life status each year, generating serious problems for disposal because of their non-biodegradability and potential fire hazard when stockpiled [84]. Use of rubber in concrete prevents these tyres from going to landfills, and creates value-added products for construction [85]. Studies related to life cycle assessments have shown that by partially replacing natural aggregates with rubber in concrete, the environmental impact of producing the concrete is lessened in several ways. Aggregate reduction leads to conservation of natural resources and protection of habitats destroyed during quarrying operations [86]. As a result of lower density, the energy required for transporting the concrete is reduced along with the loads on foundations which are both factors contributing to total carbon emissions being reduced [87]. Furthermore, combining the use of recycled steel plates with the use of waste tyre rubber within the hybrid system supports the circular economy and assists in achieving global sustainable development goals [88].

6.2 Economic Viability

The economic analysis of a rubber-steel hybrid wall system will include the total cost of initial construction, as well as life cycle expenditures which include: 1) maintenance; 2) repairs; and 3) possible post-earthquake losses. Construction costs of an initial project using waste rubber aggregate materials tend to be less expensive than using natural aggregate materials primarily because rubber waste is generally difficult to process and is readily available locally in urban environments [89]. However, processing (sizing and cleaning) of the rubber particles may negate some of the savings of the aggregate materials [90]. Although steel plates increase the initial construction costs, prefabrication and expedited construction can help to minimize the labor costs and time required to complete the project [91]. The enhanced seismic performance of the hybrid system will provide cost savings to the owner from decreased earthquake insurance premium payments, reduced anticipated loss of damages, and minimized lost income from business interruptions throughout the lifetime of the building [92]. The studies have shown that while the added cost of rubber-steel hybrid walls would be recoverable through the reduction of total life cycle costs of the structure, especially in high-seismic-risk regions where the probability of earthquake-related damage is great [93].

VII. PRACTICAL IMPLEMENTATION AND DESIGN CONSIDERATIONS

7.1 Construction Methodologies

To successfully implement rubberized concrete in construction methods will need to be adjusted from traditional practices based on the different physical characteristics of rubberized concrete materials. To assure that all rubber is evenly dispersed throughout the concrete, the mixing method used to prepare rubberized concrete should allow for a uniform distribution of lightweight rubber particles which are prone to separation when being moved and placed into a mold [94]. By using extended mixing time, adding water at a controlled rate, and using superplasticizers (to enhance the ability to place and finish the rubberized concrete) can result in a consistent mixture [95]. The methods used for

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vibration and compacting rubberized concrete have to be modified to avoid the floating of rubber particles while still allowing enough compaction so that the rubberized concrete has adequate density [96]. Surface finishing rubberized concrete is difficult because rubber tends to migrate to the surface of the rubberized concrete as it is troweled over, and therefore needs to be finished differently than regular concrete or protected by an applied coating [97]. The steel plates in a reinforced rubberized concrete composite structure have to be aligned accurately and securely anchored to allow for composite action between the reinforcing steel and the surrounding rubberized concrete. Therefore, welded dowels, mechanical fasteners, and structural adhesives must be capable of transferring interface shear loads between the reinforcing steel and the rubberized concrete without failing prematurely [98]. Before accepting the completed rubberized concrete composite structure, quality control measures must confirm the accuracy of the position of the reinforcing steel, the adequacy of the amount of concrete covering the reinforcing steel, and the effectiveness of the bond between the reinforcing steel and the rubberized concrete [99].

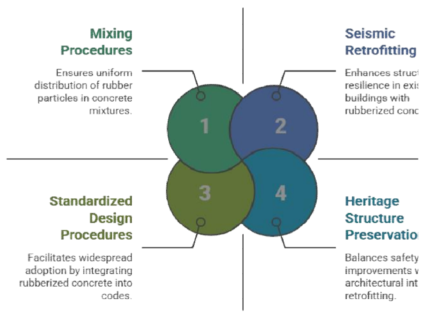

Figure 3. Implementation and Design Consideration for Rubberized Concreate. (Source: Original Image)

7.2 Retrofitting Applications

The Hybrid Rubber Steel System is highly promising for Seismic Retrofitting of Buildings Lacking Adequate Earthquake Resistance. Prior to the development of modern seismic building codes, a large number of buildings were constructed lacking sufficient shear capacity and ductility in their key structural components [100]. The hybrid rubber-steel system can be easily applied externally by attaching steel plates to building walls (using chemical anchors, through bolts etc.) and then injecting high performance grout (or replacing existing concrete) with rubberized concrete [101]. Generally, this process will include surface preparation of existing walls; attachment of steel plates using chemical anchors, or through bolts; and finally the injection of high strength grout or rubberized concrete mixture into the space between the new steel plate and the original wall [102]. As an additional benefit, the low density of the rubberized concrete provides a substantial reduction in added mass, while also providing increased damping and ductility in comparison to traditional concrete [103]. Therefore, the hybrid rubber-steel system is well-suited to the needs of heritage buildings where there are conflicting requirements to preserve the architectural integrity of the structure and improve its safety [104].

7.3 Design Guidelines and Code Development

Widespread use of rubber-steel hybrid wall systems will require standardization of design processes in addition to inclusion in the building codes. The current seismic design codes contain no specific details on how to design with rubberized concrete, or hybrid reinforcement systems that limit their application [105]. In order to develop a practical and usable design process for rubber-steel hybrid wall systems, research must be compiled into simple design expressions and detailing requirements suitable for practicing engineers [106]. Any proposed design approach must consider modified material properties due to the reduced modulus of elasticity, improved damping characteristics, and altered stress-strain response of rubberized concrete [107]. When designing steel plates to work in combination with rubberized concrete, the designer must consider composite action, potential buckling failure, and connection detail requirements unique to hybrid designs [108]. Performance based design frameworks are ideal vehicles for implementing innovative systems such as rubber-steel hybrids, since performance based design allows designers to evaluate actual seismic response of structures instead of relying on prescriptive requirements [109].

VIII. FUTURE RESEARCH DIRECTIONS

Although the study of rubber-steel hybrid walls has significantly improved our knowledge of these structures' behavior, a number of areas remain unexplored by researchers. Studies focused on long-term durability and the impact of aging effects, environmental factors (exposure to weather, chemicals, etc.) as well as continued loading will be necessary to create the basis for estimating the expected lifespan of such structures [110]. Additionally, accelerated aging protocols utilizing freeze/thaw cycles, chemical exposure, increased temperature, etc., are required to determine the mechanism(s) of degradation and estimate the durability characteristics of the structure [111]. Investigations into microstructure utilizing advanced imaging techniques will allow us to understand the bond mechanisms between the rubber and cement at the interface of these materials, and further identify possible surface treatments that enhance the load transfer at this interface [112]. In addition to surface treatments, nano-scale modification of the rubber-cement interface with materials like silica fume, graphene, or polymer coatings may provide alternative methods to improve the interface strength while maintaining the sustainable attributes of waste rubber utilization [113]. Testing programs designed to evaluate full scale structural systems (versus individual wall components), would be very useful in providing information related to system level behavior (such as torsion, interaction with foundations, etc.), and three dimensional effects [114]. Shake table testing of hybrid walls utilizing realistic ground motions and multi directional excitations would provide an evaluation of performance during actual seismic events [115]. The development of numerical models of hybrid walls utilizing advanced constitutive models for rubberized concrete and the interface behavior of steel/concrete would provide the ability to perform parametric studies of design options outside of the range of feasible experimental testing [116]. Validation of the developed models would enable fragility assessment, performance based design optimization, and the development of simplified design methodologies suitable for application in the engineering practice [117].

IX. CONCLUSIONS

A comprehensive review was conducted to examine the use of waste tyre rubber aggregates with steel plate reinforcement in shear wall systems, to evaluate their effectiveness for seismic design. The experimental results demonstrated that there is a variety of advantages to using a hybrid system to achieve two primary objectives: (1) to enhance the structural performance; and (2) to achieve environmental sustainability. Major conclusions drawn from the reviewed studies are outlined below. A partial replacement of natural coarse aggregates with waste tyre rubber at volumes of approximately 10% to 15% of total volume results in concrete with a significantly reduced compressive strength than normal concrete, but which exhibits considerably enhanced ductility and ability to dissipate seismic energy. The presence of rubber particles in the concrete introduces damping mechanisms that reduce the amount of seismic energy that is transmitted to the structure, while also reducing the rate of crack propagation and enhancing the deformation of the concrete prior to failure. Thus, the inherent brittle fracture mode exhibited by normal concrete can be modified to a more ductile fracture mode that would be beneficial for earthquake-resistant structures. Additionally, the incorporation of steel plates in these shear walls provides several additional benefits including enhanced tensile properties, more uniform stress distributions and reduced crack widths. In addition to the aforementioned benefits, the steel plates may serve as a source of external reinforcing, providing alternative load paths for lateral loads during severe seismic events, and redistributing the stresses within the concrete, thus maintaining the integrity of the wall, even after significant concrete cracking has occurred. The combined effects of the steel and rubberized concrete create a balance of materials that offer the flexibility of rubber and the strength of steel, resulting in superior seismic performance compared to either material used separately. Numerous experimental studies have shown that hybrid rubber-steel shear walls exhibit more stable and wider hysteresis loops, increased ductility factor, greater cumulative energy dissipation and a lower rate of stiffness degradation, than conventional reinforced concrete shear walls. As a result of the enhanced seismic performance, hybrid shear walls provide an improved level of earthquake resilience, reduce the potential for damage to the structure, and improve the post-earthquake functional condition of the building. In addition to the enhanced seismic performance, the elastic nature of the rubber particles provides a self centering capability of the structure after a seismic event, allowing for easier restoration of the structural serviceability after the occurrence of an earthquake. From an environmental perspective, the use of waste tire rubber in hybrid shear walls addresses the significant waste management issues associated with disposal of scrap tires, while also conserving the natural resources of aggregate materials. Therefore, the use of rubber in hybrid shear walls represents an example of the application of the circular economy philosophy and promotes the development of sustainable construction methods. However, the implementation of hybrid shear walls requires consideration of the construction techniques, quality assurance processes and the development of standardized design guidelines. Finally, the development of code provisions related to the use of rubberized concrete and hybrid reinforcement systems is necessary for facilitating the broader acceptance and implementation of this technology. Future research should address the long term durability of the hybrid shear walls, the full scale behavior of the system and the refinement of design procedures, to facilitate the transition from experimental study to practical implementation of hybrid shear walls. The information contained in the previous discussion clearly demonstrates that the use of steel plate shear walls with waste tire rubber aggregates represents a promising innovation for developing safer, more environmentally sustainable and more resilient infrastructure in areas prone to earthquakes.

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