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INFLUENCE OF CONSTRUCTION MATERIALS ON SEISMIC PERFORMANCE OF BUILDINGS AFTER ECUADOR M7.8 EARTHQUAKE

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Abstract

More than 7000 buildings were severe damaged or destroyed after the Mw 7.8 Pedernales earthquake in Ecuador, last April 16, 2016. In this paper, materials used in the construction of such buildings are studied as a possible source of vulnerability. Wooden and concrete material used for structural elements and masonry walls have been analyzed and tested (lab and SEM). The analysis included construction practices applied. Evidence found confirmed that construction materials quality is far from acceptable and construction practices applied were very poor. The use of sea sand caused very high corrosion in steel reinforcement and mylonitization of coarse aggregates used in concrete produced a very low strength material. Those facts and the non-technical expansion of existing structures were the main reason of damage and collapse of thousands of buildings.

Keywords: seismic damage, low strength concrete, sea sand, mylonitization, chloride content, building collapse

1. Introduction

More than 7.000 buildings were severed damaged or destroyed in Manabí province, Ecuador (Fig. 1), 670 people were killed, 6.300 injured and almost 30.000 people lost housing after Mw7.8 earthquake that hit the region last April 16, 2016. Damages in infrastructure and losses have been officially estimated in at least US$3.340 million dollars, and almost 70% are related to losses in buildings and infrastructure.

Fig. 1 – Map of the epicenter and PGA recorded of the Mw7.8 Pedernales earthquake at the north-west coast of Ecuador [1], and view of Pedernales City, where 80% of buildings were severed damaged or destroyed

In spite of the fact that damaged and collapsed buildings showed usual seismic failure patterns of non-ductile structures (i.e. soft stories, flat slab shear failure, plastic hinge in columns and joints, shear failure in short columns, shear and out-plane-failures in masonry walls), and spite of the evidence of strong soil response amplification in specific areas of the affected region, quality of materials and constructive processes applied seem to be also very important in the overall poor seismic performance of buildings. This research focuses on construction materials and procedures found in damaged and collapsed buildings.

2. Analysis of materials and its impact in damaged and collapsed buildings

After a survey of the affected area, and from construction materials point of view, it was possible to classify most of damaged and destroyed buildings in two main structural typologies: a) wooden structures with concrete/clay brick masonry walls and partitions and b) reinforced concrete buildings with masonry infill (concrete/clay brick) walls.

2.1 Wooden structures with masonry walls and partitions

This group refers to all structures having wooden columns, beams, floors and roof system, using wooden partitions or a combination of clay bricks and concrete block units as components of masonry partitions walls. This type of construction is relatively old and has typically some external portals, permitting people´s circulation on streets (Fig. 2). In some cities of Ecuador, and for some specific areas (commercial areas typically), external portals are mandatory according to some local architectural regulations. Wooden partitions are commonly using wooden cane with some internal wooden structural elements for giving stability under vertical loads. Masonry walls instead, are made by clay bricks in a vertical position (it means that horizontal side of a brick has the shortest area, which is in contact with other bricks for conforming wall, procedure that is not recommendable at all due to instability problems of the unit and of the wall panel). Sometimes such walls are built using concrete blocks or a combination of clay bricks and concrete blocks. Both wooden and masonry walls are usually covered by cement mortar (Fig. 2).

Fig. 2 – Typical wooden structures in the area, using wooden columns, beams, floor and roof system, and wooden cane, clay brick and/or concrete block units for masonry walls and partitions. External portals are common in order to permit people´s circulation on streets

One important aspect related to this type of construction, especially in some commercial areas of the cities in the region, is the use of wooden structural columns surrounded by 6cm wide clay bricks, creating an air chamber of 8 to 15cm wide between columns and bricks (Fig. 3). Such air chamber is sometimes filled by sand. At the end, bricks are externally covered by cement mortar and painted. Therefore, from outside there is a false sense of the existence of 30 to 50cm wide concrete columns. This false columns are part of the external façade of the building creating a new/modern building style. Apparently, the purpose of this practice is to give a false sense of safety, permitting to expand the original size of the building in horizontal and vertical way, avoiding municipality control and increasing seismic vulnerability exponentially.

Fig. 3 – (Left) False clay brick column surrounding an existing old and deteriorated wooden column, covered by cement mortar and paint. (Right) Some non-engineered expanded constructions creating columns without continuity in all floors

In general, this type of construction belongs to the so called "non-engineered" structures, which has been built directly by the owners, using labor without technical supervision. Many of them are old; wooden frames are deteriorated, cracked, with evidence of insect attack, therefore, losing its main resistance (Fig. 3). Many of them have suffered horizontal and vertical expansions in time, sometimes of several floors. In some specific cases, it is also possible to find evidence of some non-engineered strengthening works, creating new reinforced columns and beams for building a new floor or floors over an existing wooden structure, not showing continuity from the bottom to the top of the structure (Fig. 3).

It is possible to conclude that this type of buildings is highly vulnerable to seismic actions. It was expected several great failures in this typology in the area. Earthquake permitted to discover this vulnerability, as it is possible to observe in Fig. 4, where not only wall failures occurred but also the actual grade of degradation of wooden materials in columns, beams and connections were observed, perhaps informing that those buildings were at the end of their service life, before the seismic event.

In other cases, low floor stiffness, masonry weight and very poor connections between structural wooden elements were factors affecting dynamic response and causing collapse of some wooden buildings. In Figure 4 and 5 it is possible to observe some damaged wooden structures having a combination of thin clay bricks and concrete block units, creating slender partitions covered by cement mortar made using sea sand, without engineering considerations. Out-of-plane masonry failures were frequently found.

In the case of moderated damaged wooden structures, it is possible that dynamic soil response of the area and/or better structural configuration helped to avoid heavy damage or collapse. Nevertheless, such type of vulnerable buildings should be carefully assessed in order to avoid future damage or collapses in future seismic events.

Fig. 4 – Grade of deterioration of wooden elements discovered after earthquake. Perhaps, service life ended before the quake

Fig. 5 – Damaged wooden structures with slender partitions made by thin clay bricks and/or concrete blocks

2.2 Reinforced concrete structures with masonry infill walls

This group refers to all structures having reinforced concrete moment resisting frames with masonry infill walls (using clay bricks and/or concrete blocks) and reinforced concrete slabs used in floor and roof systems.

This group of buildings has presented strong seismic damage and collapses. Their analysis should be made not only from the engineering, but also from social point of view, including the understanding of the education, culture, customs, attitude and behavior of population living in the affected cities.

2.2.1 Social and economic aspects related to building collapses

After some important economic development during the last decades in many cities around the epicenter, due to success of tourism, fishing, exports and other related industries, there was a high pressure in the housing market, hotel infrastructure, vacation facilities, roads, etc., which transmitted such pressure to other economic activities such as services, transportation, food, commercial exchange, etc., attracting people from rural areas to cities, increasing number of family members and housing, commercial and financial buildings demand. Under those conditions, existing structures (some of them built using engineering design and construction considerations) were expanded in both, horizontal and vertical way, in order to try to attend the mentioned demand. In most cases, existing building owners did not considered technical advice and increased construction area without thinking on earthquake risk. One or more floors were built over existing constructions, without any seismic risk consideration. There are a lot of examples of dramatic collapses of residential, commercial and hotel buildings after the earthquake, two of the most famous are showed in Fig. 6. The figure at the left shows the most important hotel building in Pedernales, which had only two floors years ago but it had five before the earthquake. The figure at the right shows a commercial building in Portoviejo presenting the same problem pattern; its collapse caused 92 fatalities (entire families) after the earthquake.

Fig. 6 – Hotel in Pedernales (left) and commercial building in Portoviejo (right). Both were expanded by the owners and converted from low rise to medium rise buildings without engineering considerations. The building at the right caused 92 fatalities (entire families) due to its collapse after the earthquake

2.2.2 Concrete and steel bars as building materials

Fig. 7 shows the typical type of concrete used in damaged and collapsed buildings in the area. Evidence of high percentage of coarse aggregate with a high rate of segregation and lack of compaction can be found. The use of sea sand as total or partial fine aggregate in concrete mixes was noted. The combination of those factors with others: low water/cement ratios, high porosity and chloride content have provoked an important grade of corrosion (even total destruction) of steel bar reinforcement.

In Fig. 8 it is possible to observe the strong high corrosion level of the steel reinforcement in an aggressive environment (smooth and deformed steel bars inside a high porosity concrete made using sea sand in a coastal region). In some cases, corrosion is in so highly advance stage that all steel reinforcement has been converted into iron oxide and it was possible to completely destroy column steel bars using hand fingers. In such cases, reinforced concrete was converted into plain concrete and collapse of structures under earthquake was more than expected.

Fig. 7 – Characteristics of concrete in damaged and collapsed structures. (Up-left) Large coarse aggregate with high segregation and large amount of mortar. (Up-right) Detached concrete coating with low amount of mortar, showing very low or lack of adherence with steel deformed bars. (Down) Large amount of course aggregate with very few mortar

Fig. 8 – Strong corrosion in steel reinforcement (deformed and smooth bars) in old and new structures. Column steel bars can be destroyed completely using hand fingers

2.2.3 Laboratory test and obtained results

In order to confirm the preliminary field observations, samples of collapsed buildings were obtained for testing. ASTM C42/C42 M-13 Standard Test Method for Obtaining and Testing Drilled Cores and Sawed Beams of Concrete [2], has been applied in order to obtain sample cores and testing. ASTM C1152/C1152 M-04 (Reapproved 2012) Standard Test Method for: Acid-Soluble Chloride in Mortar and Concrete [3], was applied in order to obtain chloride content of concrete and to make a comparison with current standards. Chloride content was confirmed using a scanning electron microscopy SEM analysis. Finally, ASTM C642-13 Standard Test Method for: Density, Absorption, Voids in Hardened Concrete [4], was used in order to obtain concrete physical parameters for characterization. All test were performed in PCH Ltd. Lab, with exception of the chloride content test and SEM analysis, made in Universidad San Francisco de Quito Labs.

A sample of the chloride content results obtained are described in Table 1 and compared to maximum allowed limits of ACI-318 Committee [5], considering a concrete with exposure category C2 (ACI-318-14, Section 19.3.1). For such exposure category, maximum limit of water-soluble chloride ion content is 0.15 as a percentage by weight of cement. For calculations, a cement content of 330kg/m^3 was adopted from the experience related to this kind of concrete produced between 15 to 40 years ago, and from correlations with the strength test results (discussed later in this paper). Therefore, maximum chloride content for this type of concrete should be no more than 0.495 kg/m^3, in order to protect reinforcement and to assure reinforced concrete durability.

Table 1 – ASTM C1152-12 average test results for chloride content in collapsed building concrete samples, in cases where steel corrosion was evident

City	Location	Coarse Aggregate (g)	Mortar (g)	% of mortar in concrete	% chloride content in mortar	% chloride content in concrete	Concrete density (kg/m3)	Chloride content in concrete (Kg/m3)*	Times in excess of ACI limit of chloride content (+)
Manta	Tarqui 1 – Hotels	391,6	313,7	44,5	0,221	0,098	2295,36	2,26	4,6
Manta	Tarqui 2 – Schools	865,6	733,3	45,9	0,976	0,448	2374,23	10,63	21,5
Portoviejo	City Center - Hotels	446,7	427,3	48,9	1,250	0,611	2419,19	14,78	29,9
Portoviejo	City Center- Magisterio area	434,4	526,4	54,8	0,407	0,223	2322,21	5,18	10,5

* Cement content adopted 330Kg/m3

\+ Limit of maximum chloride content allowed by ACI318: 0.15% by weight of cement (0.495kg/m3)

According to the results, chloride content of samples could exceed the ACI 318 limit in until 30 times. Those values are consistent with the extremely high level of corrosion and degradation of steel bars observed. This problem was confirmed by analyzing samples using a SEM analysis. Fig. 9 is showing a fine aggregate particle, which surface contains Mg, K, Na and Cl in more than 5% atomic ratios.

This aspect is of great concern, due to the fact that, even if there are many buildings that suffered lower or negligible seismic damage after the earthquake, their integrity is not warranted and could suffer damage and collapses in future seismic events with even lower intensity.

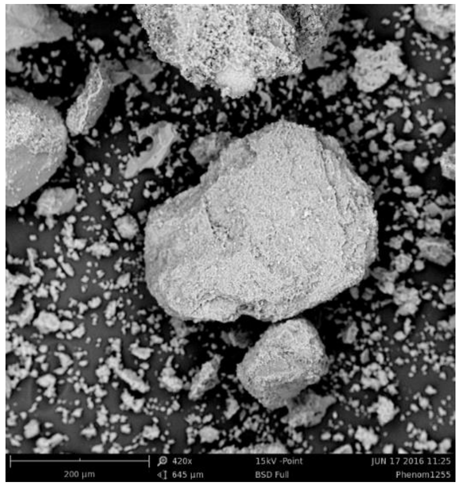

Fig. 9 – SEM analysis of a fine aggregate particle in mortar samples of collapsed buildings. Its surface has shown Mg, K, Na and Cl of about 5 to 8% atomic ratio.

After collecting information about construction processes and construction materials used in the region, it was possible to know that the use of sea sand in the production of concrete is very normal, even for constructions where a professional (architect or civil engineer) was in charge. Regarding fine aggregate material for concrete, common practice in the region considers a mix of sea sand and mining sand which are exploited in some areas that were also under the ocean million years ago. Fineness modulus of fine aggregate samples obtained are so lower (around 1.1), which dramatically increase water demand and water/cement ratios, increasing porosity and decreasing strength. Therefore, not only the granulometric distribution of used sand and other physical characteristics are not adequate, but also organic and chloride content of sea sand have created problems in concrete strength, durability and a highly corrosive environment for steel reinforcement.

Table 2 shows ASTM C642-13 average test results for density, absorption and voids content in the same reported concrete samples described before. Porosity and void content are really high, facilitating environmental attack and steel corrosion. Results are also showing evidence of high water/cement ratios used in concrete mixes, perhaps over 0.7-0.8, especially after considering voids volume results that are almost two times the voids content of a standard concrete mix with proper design, compaction and curing (that usually has about 10-12%).

Table 2. ASTM C642-13 average test results for density, absorption and voids in hardened concrete samples

City	Location	sss weight 1 (g)	sss weight 2* (g)	Submerged weight (g)	Dry weight (g)	Absorption 1 %	Absorption 2* %	∂ ss 1 g/cm3	∂ ss2 * g/cm3	Apparent ∂ ss g/cm3	Permeable void volume %
Manta	Tarqui 1 - Hotels	2266	2277	1285	2031	11,57	12,11	2,28	2,30	2,72	24,80
	Tarqui 2 - Schools	3456	3483	2016	3194	8,20	9,05	2,36	2,37	2,71	19,70
Portoviejo	City Center - Hotels	1432	1437	843	1340	6,87	7,24	2,41	2,42	2,70	16,33
	City Center - Magisterio	1587	1600	911	1444	9,90	10,80	2,30	2,32	2,71	22,64

* Weight sss 2 is related to sss weight after boiling

Table 3 shows average compression test results of 3 inch diameter (7.5 cm) concrete cores obtained from the same collapsed buildings according to ASTM C42-13 standard. Core samples were obtained from structural elements sections where cracking and any structural damage were not found. Those concrete samples are between 15 to 40 years old, where ASTM C-150 Type I Portland cement was available (today such cement is not available in the local market). Accordingly to the results, average compression strength of concrete at the age of 15 to 40 years is just over the minimum strength required by ACI 318 at 28 days (21 MPa) for structural concrete. This low resistance is consistent to the characteristics of concrete (low water/cement ratio, high porosity and low level of compaction) described before.

Table 3. ASTM C42-13 Test method for obtaining and testing cores of concrete applied to concrete samples

City	Location	Core #	Diameter d (cm)	Height h (cm)	h/d	Correction factor	Area A (cm^2)	Load (kg)	fc (kg/cm^2)	corrected fc (kg/cm^2)	Average fc (kg/cm2)
Manta	Tarqui 1 - Hotels	1	7.5	11.9	1.59	0.96	44.18	9749.0	220.7	211.8	
		2	7.5	10.6	1.41	0.94	44.18	10809.0	244.7	230.0	**220.9**
	Tarqui 2 - Schools	1	7.5	10.6	1.41	0.94	44.18	8089.0	183.1	172.1	
		2	7.5	10.1	1.35	0.93	44.18	10407.0	235.6	219.1	**209.3**
Portoviejo	City center - Hotel	1	7.5	8.8	1.17	0.90	44.18	10288.0	232.9	209.6	
		2	7.5	7.5	1.00	0.86	44.18	13609.0	308.0	264.9	**237.2**

On the other hand, a very interesting effect was also detected in many concrete core samples obtained. Mylonitization (existence of fine materials around coarse aggregates due to the formation of some types of rock in a strong tectonic deformation environment) around coarse aggregates was detected, creating an isolated interphase between aggregates and cement paste, not permitting to have a homogeneous concrete core. This phenomenon caused that concrete samples in many buildings be destroyed during drilling, at the time of the extraction or at the time to prepare and cut samples before testing. When it was possible to test such samples, many cracks were found in such interphase between coarse aggregate and cement paste. In Fig. 10 it is possible to observe mylonitization effect in samples before testing. Sometimes, when this effect was strong, it was possible to destroy the sample using hand fingers or a pen. A view of concrete inside a column after core extraction is also presented in Fig. 10, demonstrating mylonitization effect that dramatically affected concrete integrity. This problem has a tremendous impact in reinforced concrete buildings in the affected area.

Fig. 10 – Mylonitization of coarse aggregate in concrete core samples before testing (left). Mylonitization effect inside a structural column after core extraction, showing tremendous impact in concrete integrity (right)

After testing, compression failure was governed by cracks in that problematic interphase, causing very low strength results, as low as 8-12 MPa. Cracks in the mentioned interphase was also observed in many reinforced concrete structural elements in many damaged buildings (Fig. 11). Sometimes, undamaged mortar cover is hiding internal concrete cracks in the core. This finding means that many buildings could be classified as undamaged and even have internal concrete damaged, increasing seismic vulnerability dramatically. If the earthquake had have few more seconds in duration, statistics of heavy damaged and collapsed buildings could have been much higher.

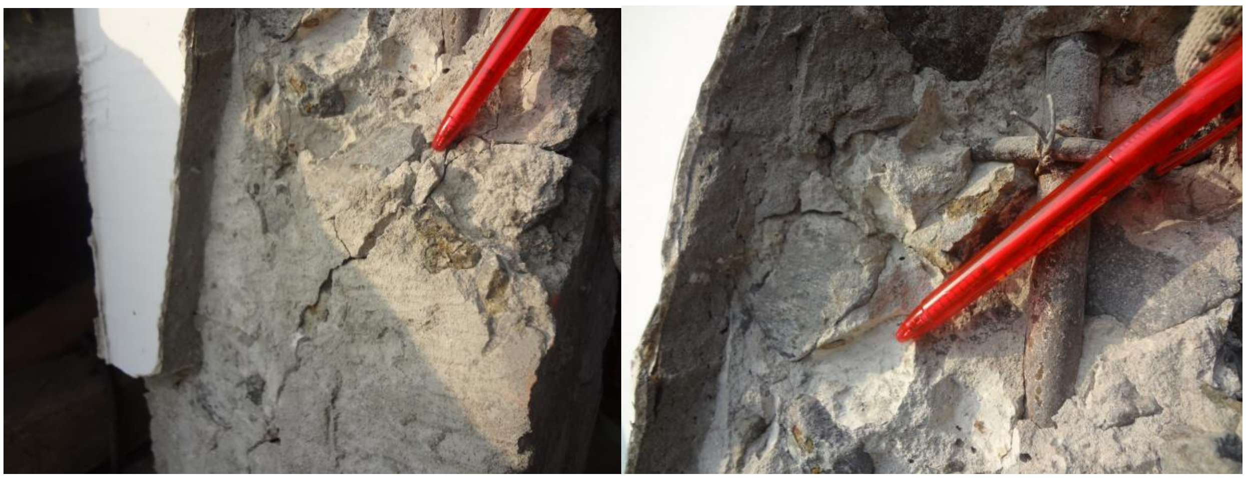

Fig. 11 – Internal concrete cracks covered by undamaged wide mortar cover, hiding mylonitization effect in concrete columns of damaged buildings

2.2.4 Concrete block units for masonry walls

Fig. 12 shows characteristics of concrete block units used for masonry walls. They seem to be handcrafted, using the same type of concrete described before, sometimes with the addition of volcanic rocks (pumice) as a coarse aggregate. Fig. 12 also shows incomplete mortar works between block units, weakening walls. It is usual to find very long and high slender wall panels without bracing system for mitigating out of plane failure risk.

Fig. 12 – Characteristics of concrete block units used for masonry walls. Thin masonry walls with incomplete mortar handwork between units and very long and high masonry panels without bracing system.

3. Conclusions

This paper refers to the importance of materials and construction procedures in the seismic behavior of damaged and collapsed buildings in the areas affected by the Mw7.8 Pedernales earthquake in Ecuador. Without any doubt, the great magnitude of the earthquake and the strong soil amplification effects found in the affected areas could be some of the factors that explain the dramatic damages and collapses of buildings. However, physical evidence found and laboratory test demonstrated that materials and construction quality are also key factors (in some cases, the most important) for explaining poor seismic behavior of thousands of buildings.

It is also demonstrated that materials durability and strength properties are questioned, in both wooden and reinforced concrete buildings. Wooden structural elements have been covered by false clay brick walls or by finishes, perhaps to create a false sense of safety and to avoid authority control for expanding buildings size. The earthquake permitted to discover the actual poor condition of wood. Service life of many wooden structures (damaged or not) seem to be ended even before the seismic event. On the other hand, very high chloride content of concrete (due to the use of sea sand as fine aggregate in concrete mixes) with high porosity level have caused a very strong level of corrosion in steel bars. In some cases, there are only traces of steel reinforcement inside concrete structural elements. Therefore, reinforced concrete could be considered as plain concrete and seismic vulnerability of buildings results dramatically high. Durability of materials and hence, structural safety in time, are not considered by building owners and some contractors.

A very interesting aspect was the mylonitization effect that created an isolated transition interphase between coarse aggregates and cement paste, decreasing dramatically concrete strength. This effect was the reason of many seismic damaged and collapsed buildings. However, it also creates a dramatic effect on the actual seismic vulnerability of survivor buildings that could be classified as undamaged, because it was demonstrated that concrete failures could exist even undamaged mortar cover was detected in many structural elements in many buildings hiding the internal problem. This is a very important issue for many thousands of survivor buildings in the affected area. Coarse aggregate mines must be investigated immediately, in order to detect the origin of such contaminated materials for avoiding its use in the future.

After the earthquake, re-construction phase will be implemented, being an opportunity to avoid re-construction of seismic vulnerability, to enhance construction materials and procedures in the region. Therefore, training programs for workers and for professionals are urgent, including the correct application of the current 2015 Ecuadorian Seismic Code requirements. Maximum limits in chloride content and in water/cement ratio (0.45) in the concrete production shall be emphasized in training programs.

Procedures for construction and materials quality assurance also have to be implemented and regulated by national and local authorities, and all professionals, workers and owners shall understand their importance. In this regard, the use of sea sand (from the ocean or from areas that were under the sea years ago) for concrete production must be prohibited immediately.

It is also very important to analyze the actual structural safety of those buildings which presented light or even negligible seismic damage. It is possible that materials condition of such buildings could not assure structural safety during the next seismic events, even if those events were lower in intensity than the 2016 Pedernales Earthquake.

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