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HIGH-STRENGTH CONCRETE (HSC) MATERIAL FOR HIGH-RISE BUILDINGS

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ABSTRACT

Successful examples of high–rise buildings in the world are obvious evidences that the use of high–strength concrete is nowadays reality in construction worldwide. Whether focus on high–rise buildings up to 15– 24 storeys, or the super tall high–rise buildings that are few hundred of storeys high, high–strength concrete of different qualities is the unavoidable choice in search for structural material. If technology development and economic efficiency opened up a gate to high–strength concrete towards wider market, high–rise buildings for sure enhanced benefits and abilities of high–strength concrete as commonly available structural material. Use of such environmental friendly, structurally safe and very resistant material enabled idea and concepts of vertical cities and vertical living. Another factor in definition of high–strength concrete is also a demand for specific strengths or performances of concrete. In the specific case of the USA or some rapidly growing Asian countries or cities, 95 MPa high–strength concrete is available in most of concrete plants, and at same time it is economically and cost efficient. On the other hand, situation in Balkan area is totally opposite. Abilities to use high- strength concrete in this area is not even adequately researched, and the top limit of concretes' strength may appear to be up to 60 MPa, which corresponds to relatively weak economical and cost efficiency.

1. INTRODUCTION

It is hard to define high–strength concrete (HSC) with one unique number, or create any strict border between conventional normal strength concrete and high–strength concrete. As long as achieved concrete or target strength is about the same quality as the local material, curing conditions, size and age of testing specimens, it imposes the fact that nor unique nor unified definition of high–strength concrete is neither possible nor necessary. Another factor in defining ranging lines of high–strength concrete is also a demand for specific strengths or performances of concrete. In the specific case of the USA or some rapidly growing Asian country or city, 95 MPa high–strength concrete is available in most of concrete plants, and at same time it is economically and cost efficient [6].

On the other hand, situation in Balkan area is totally opposite. Abilities to use high- strength concrete in this area is not even adequately researched, and the top limit of concretes' strength may appear to be up to 60 MPa, which corresponds to weak economical and cost efficiency. However, in different standards there are some differences in classifications of concrete up to the characteristic compression strengths. According to BAS EN 206:2014 [12], normal–weight and heavy–weight concretes are divided into sixteen classes according to their compressive strengths; high– strength concrete is in range between C55/67 and C100/115.

Terms high–strength concrete and high–performance concrete were commonly used as synonyms, which was acceptable at the early beginnings. However, in the contemporary concrete technology, this interchangeable use of the two terms is not acceptable.

High–strength concrete commonly refers to the increase in compressive strength of concrete, while high–performance concrete refers to the increase of all concrete's properties, with accent on mechanical properties, durability, workability, permeability etc. which is more than just increase of strength.

Commonly, the periphrastic high–strength concrete is introduced as new material or as a result of new technological development. Although such periphrasis may be taken as correct, term high strength concrete and practice of creating high–strength concrete occurred many decades ago. Dating back to 1950s, concrete with compressive strength of 34–35 MPa, was considered to be high–strength concrete. However, when compared to contemporary daily routine in concrete solutions, designed compressive strength of 34–35 MPa, at 28th day of age is one of the most common examples of conventional or so called normal strength concrete.

More specific and more scientific approach to the subject of high strength concrete occurred in the 1960s. Newly developed high–strength concrete with compressive strength of 41 to 52 MPa, rapidly spread through the construction sites across the USA. For high–strength concrete technology, sixties of the last century were crucial turning point because all experimental studies of technological development were aiming for the achievements of the desired results.

In the early sixties, Japan was a place where the first superplasticizers were developed. Formaldehyde condensates of beta naphthalene sulfonates, were developed by Dr Hattori. These superplasticizers had primary function to reduce water demand in production of high–strength concrete. Product created was named Mighty 150, which could decrease water usage up to 30 percent. Along with superplasticizers, use of another supplementary material for high–strength concreting developed in this period was silica fume or so called microsilica; micro–filler in between cement particles, a by-product of Ferro–alloy industry was first introduced by German Doctor Aignesberger.

Although invention of superplasticizers and silica fume took place in Japan and Germany, most of the credits in HSC development for wide use went to Chicago, United States. During the early sixties, Chicago was a place which accelerated development of high–strength concrete and increased that day available concrete's compressive strength of 35 MPa to 41 MPa for 40–storeys high–rise buildings. An engineering step forward pioneered the use of high–strength concrete in Chicago on the Outer Drive East high–rise building (*Figure 1 – right*).

The USA, also constructed numerous bridges, river dams, marina piers and terminals; however their main focus was on structuring of high–rise buildings, multi–storey garages, shopping malls etc. For instance, it was almost mandatory for high–rise buildings in Chicago to be structured with high–strength concrete. In 1972, from previous 41 MPa, concrete's strength already increased to 52 MPa for structuring of 52–storey Mid–Continental Plaza. It is important to mention that production and application of high–strength concrete used to structure Mid-Continental Plaza, was more of an economical choice rather than a solutions. Achievable strength of concrete and all performances of concrete were increasing year after year with correspondence to cost efficiency, and due to the development of chemical admixtures and other supplementary materials; the result was of 74–storeys Water Tower Palace, in 1976. Water Tower Palace, was the world’s highest high–rise structure in that period, designed as concrete structure reaching compressive strength of 62 MPa [6].

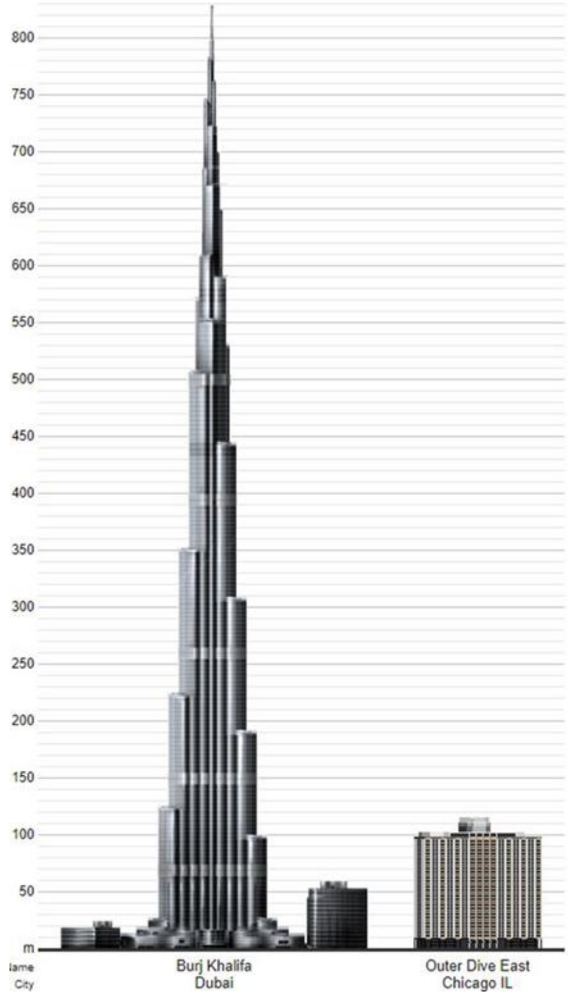

Figure 1. The Last Completed Super High–Rise, Burj Khalifa, 2010 (left) and the First Completed High- Strength Concrete High–Rise, Outer Drive East 1963 (right) [13]

After all, American Concrete Institute can take all credits for the rapid development of high–strength concrete and actual exposing of high–strength concrete to a wider market for application in most of the high rise buildings worldwide.

Nowadays, high–strength concrete is in wide use all around the developed world, and it is more than common to find concrete plants which can catch up with the production of concrete with compressive strength of 95 MPa, on daily basis [6].

2. ADVANTAGES AND DISADVANTAGES OF HIGH-STRENGTH CONCRETE

High–strength concrete was developed as better and as structural material of higher quality when compared to normal strength concrete. Therefore it has many benefits, both in performance and cost efficiency, so HSC advantages are reduction in structural element size, reduction in amount of longitudinal reinforcement and compression members, focusing on slenderer columns, higher strength and better performance leads to larger spans and decrease of total number of beams, columns etc., decreased time necessary for concrete’s formwork due to early strength development, decrease in concrete cover due to lower permeability, long

performance under the most critical action combinations, lower creep and shrinkage with higher resistance for freezing and thawing, increased resistance to very aggressive environments, decreased axial shortening, buckling of supporting elements, increased rentable space, due to slenderer and thinner elements, but also decreased number of supporting elements due to larger spans, decreased permanent action of self–weight of structure, decreased maintenance and repair costs and greater stiffness due to higher modulus of elasticity with high compressive and flexural strengths.
Although high–strength concrete has many advantages as a material, it also has disadvantages which may occur due to some impurities or even as a consequence of some advantages mentioned above. High strength concrete disadvantages are bond strength between cement paste and aggregate does not increases with the same acceleration as compressive strength, high–vibration are required for better compaction, and to exclude possible segregations, minimal concrete cover for reinforcement protection may prevent the use of maximum benefits in reduction of element sizes, available prestressing may be inadequate for the maximum use of high–strength concrete's strength, high–strength concrete requires very detailed, precise and careful material selection and does not accept any impurities and due to low W/C ratio, high–strength concrete requires special curing and installation or placement.
There is a possibility of decrease in stiffness, whereas modulus of elasticity does not respectively increase with concrete's strength, therefore use of high–strength concrete may provide slenderer elements but with lower stiffness which may lead to stability problems, whereas solution lays in very precise choice of structural systems [6].

3. CONSTITUENTS OF HIGH-STRENGTH CONCRETE

Like a conventional normal–strength concrete, HSC also contains constituents, or in other words raw materials. Materials which participate in high–strength concrete proportioning are: supplementary cementitious materials, fly ash, silica fume and some other mineral admixtures, aggregates of the best quality, and of high compressive strengths which include dolomites, granites, quartz etc., as well as superplasticizers or some other types of chemical admixtures.
It is important for high–strength concrete to have raw materials of the highest quality without any compromises for marginal or lower qualities. If raw high quality materials are well proportioned and combined, it is possible to produce high–strength concrete with long lasting compressive strength and other mechanical properties.
Generally, all types of Portland cement proved to be suitable in production of concrete of compressive strength up to 60 MPa at the 28^{th} day of age. However, to achieve higher strength with respective increase in performance and workability it is necessary to design and study reactions between additional chemical and mineral admixture.
Along with Portland cement, use of Blended hydraulic cement in production of high–strength concrete is common. Blended hydraulic cement is mixture of Portland cement and other supplementary cementitious materials, also named mineral admixtures. Benefits of Blended hydraulic cements lay in lower rate of heat development, higher strength, lower permeability, increased durability and overall performances.
Credits for accelerating the development of high strength concrete technology go to the mineral admixtures, usually denoted as supplementary cementitious materials (SCM). These are the materials which developed and increased concretes' performance and strength of both fresh and hardened concrete. Generally, mineral admixtures are siliceous and alumina siliceous materials which with the addition of water chemically react with calcium hydroxide in order to perform cementitious properties. The most common types used in preparation of high–strength concrete are fly ash, cement slag and silica fume (*Figure 2*), while less in use are ultra-fly–ash, volcanic ashes, met-kaolin, diatomaceous earths and calcined natural

pozzolans. Benefits of blended hydraulic cement in lower permeability, higher strength, and lower heat of hydration are also benefits of mineral admixture (SCM).

Figure 2. Common Mineral Admixtures – Supplementary Cementitious Materials for High-Strength Concrete [14]

Fly ash is the most common type of SCM and by–product of combustion of pulverized coal; it is spherically shaped and glassy residue. Fly ash is commonly added to all concretes for higher performances. When combine fly ash and slag cement with Portland cement, it may create concretes with compressive strengths of 70 MPa.

Silica fume or micro silica is a by–product of silicon metals and ferrosilicon alloys, generated during reduction of quartz in the production of silicon metals and ferrosilicon alloys. This ultra–fine non–crystalline by–product, enabled widespread of high–strength concrete and the ability to produce ultra–high–strength concrete at all.

Generally, silica is described as grey to black dust. Silica fume is available in forms of raw powder, water based slurry, densified or palletized. Silica fume in form of densified powder is the most common practice of adding silica directly to concrete mix. Silica fume grains are approximately 100 times smaller than Portland cement grains with sizes of 0.1 to 0.3 μm. Although silica fume or micro silica has numerous advantages, its fineness may require higher percentage of water which may cause a decrease in workability and other desired properties if high–range water reduction admixtures are not added.

The principle of micro–filling with silica fume benefited in strengthening the bond between coarse aggregate and concrete paste, with the ability of achieving compressive strength of over 105 MPa. Silica fume also tends to be efficient in reduced demand of other cementitious materials, for instance 1 kg of silica fume may replace 2 to 5 kg of cement, while the remaining content of water.

Production of high–strength concrete would be impossible without superplasticizers such as high–range water reducers, retarders etc. As SCM (supplementary cementitious materials/ mineral admixtures), chemical admixtures improve both fresh and hardened concrete. Without chemical admixtures, even the ability for transport, placement and curing of conventional normal–strength concrete would be questionable, and therefore lack of chemical admixture in high–strength concrete would make high–strength concrete impossible.

High–range water admixtures as more common superplasticizers (HRWR) decrease W/C ratio, but it is important to determine correct dose and type of the admixture. Thus, HRWR increase strength, with decrease W/C ratio, while maintaining slump constant, but also increase slump while maintaining W/C ratio.

When compared to conventional normal–strength concrete, W/C ratio in high–strength concretes is lower varying from 0.22 to 0.40. However, it is important to analyse whether the certain decrease in W/C ratio is necessary and whether it leads to the requested increase of concrete's strength and performance.

The highest percentage of concrete's volume goes to aggregate volume. Selection of the appropriate aggregate is very important; in high–strength concrete, the best quality and the strongest aggregates are required. What effects aggregate is its density, grain size composition, shape and texture of the aggregate surfaces. In high–strength concrete rough textured and angular aggregates increase mechanical cement paste–aggregate bond and therefore such aggregates are more workable in high–strength concrete. Trap rock, granite, dolomite and quartzite are mineralogy types of aggregates, suitable for high-strength concrete.

Although high–strength concrete has lower fire resistance than normal strength concrete, it still has higher fire resistance than any other structural materials and becomes economically efficient solution able to improve its fire resistance. [4]

According to the most of the nowadays standards, high–strength concrete and ultra–high-strength concrete are leading concretes with compressive strengths of above 50 MPa and 150 MPa respectively. Many countries are somehow limited to maximum concrete strengths up to 50–60 MPa due to lack of demand for higher performance and higher strength concretes or because of the lower rate of development. However, areas under rapid and constant construction and development in vertical directions, routinely produce concretes with compressive strengths of over 80 and 100 MPa. The USA, Canada, Singapore, China, Malaysia, UAE are countries and areas with the highest usage of high–strength concrete. Such fact is not surprising because these are the areas with the largest construction sites dedicated to high–rise construction and way of living. In circumstances, where daily human habits are lifted way above the ground, safety comes first. High–strength concrete showed its power in ensuring necessary safety in high–rise buildings, providing safety and comfortable living environment, with its high rate of resistance to any possible structure's daily displacements due to wind actions, seismic actions, or high–rate of resistance in cases of emergencies such as fire or progressive collapse, where the structure itself enables sufficient time for safety evacuation [6].

4. HIGH-RISE BUILDINGS OF HIGH-STRENGTH CONCRETE

Possibilities in structuring of high–rise buildings out of high–strength concrete are best described on examples of Burj Khalifa (*Figure 1 - left*), Petronas Twin Towers, Taipei 101 (composite structure–steel and high–strength concrete), etc. Magnificent architecture and breath-taking heights were enabled without any concessions by virtue of high–strength concrete. High–strength concrete in these examples showed limitless abilities in concrete technology, and at same time provided sufficient safety to occupants and inhabitants. Besides mentioned, there are numerous examples of high–rise buildings which represent great examples of concrete technology development.

Eureka Tower in Melbourne, Australia, a 91–storey tall high rise building is structured as outrigger system, and entirely erected with high–strength concrete (*Figure 3*). It is designed with central core, perimeter columns, shear walls and continuous outrigger with thickness of 30 cm. This choice of high–strength concrete as structural material, decreased cross sections of structural elements and increased rentable area of floor plans.

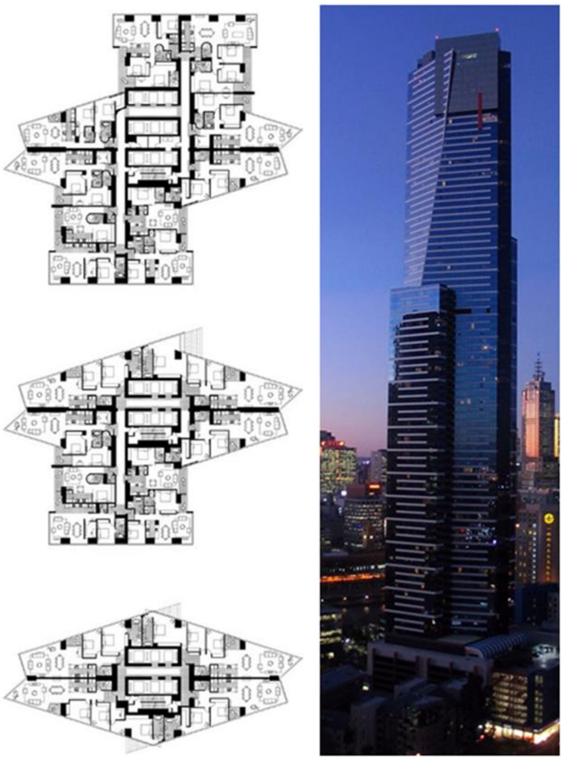

Figure 3. Eureka Tower Characteristic Floor Plans
26-52 Storeys (left – top), 53-65 Storeys (left – mid), 66-88 Storeys (left – bottom), Black Hatch Stands for High–Strength Structural Elements and in 2006 (right) [15]

Another example is Baiyoke-2 Tower in Bangkok, Thailand (*Figure 4*), a 90–storeys high–rise building which was designed with the desire to break the world record as the tallest hotel and the tallest high–strength concrete building. This 90–storeys structure was constructed with high–strength concrete, and represented turning point in concrete technology seen up to that day in Thailand. Concrete columns, and concrete central core, as well as concrete slabs, were built out of high–strength concrete with compressive strength of 60 MPa up to 65–storey. Final 25 storeys were constructed out of concrete with compressive strength of 50 MPa.

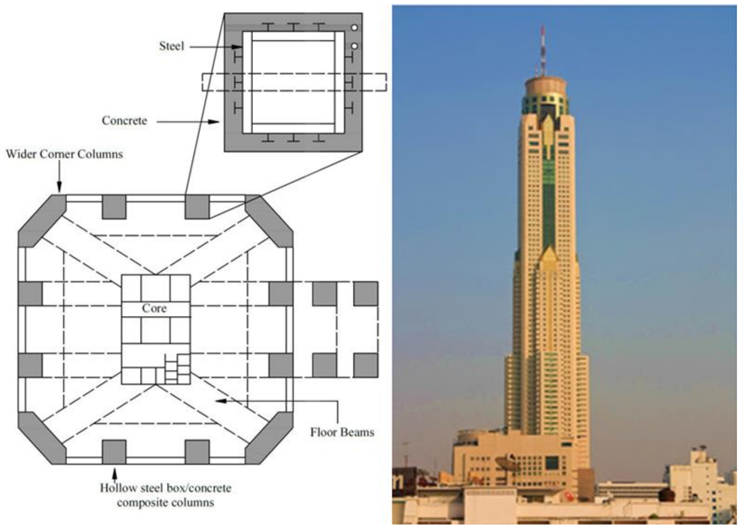

Figure 4. Baiyoke Tower 2 [16, 17]

Although Europe is a few steps behind the USA, Canada, China and others in vertical expansion, Holland, Finland, Germany, Denmark and Norway are European countries which have practice in production and use of high–strength concrete for specific purposes in construction of high–rise buildings.
Germany pioneered the use of high–strength concrete through the Trianon, high–rise building in the Westend of the Frankfurt am Main, in 1992 (*Figure 5*).

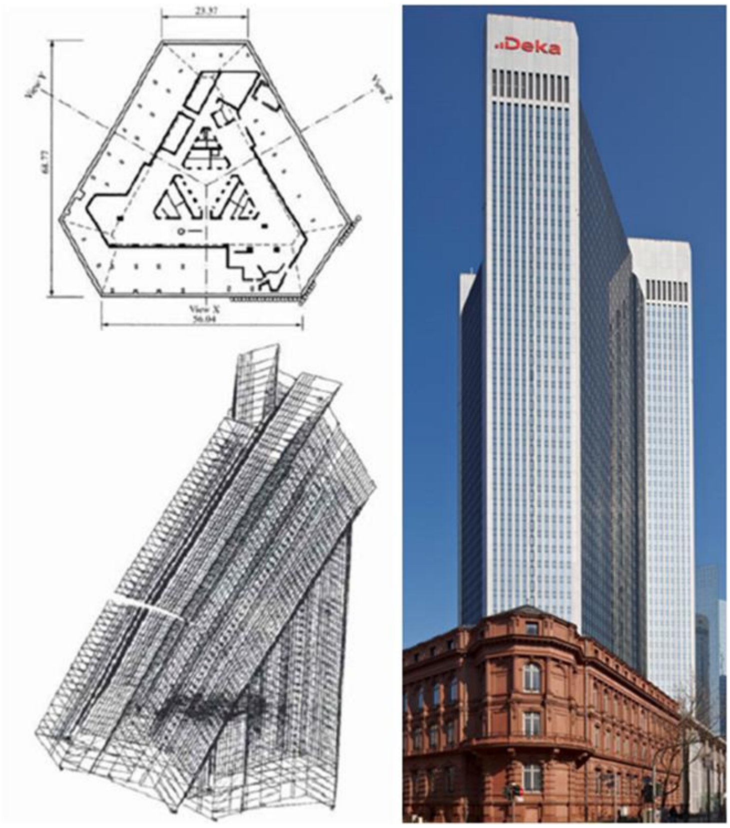

Figure 5. Characteristic Floor Plan of Trianon Building (left–top), Schematic Scenario of Possible Collapse (left–bottom) and Trianon Building, 1992, completed (right) [18,19]

This high–rise building with final height of 186 meters has 47 storeys above and 4 storeys below the ground level. High strength concrete B 85, was used for four main columns 54 cm wide and partially for shear walls. The rest of the structure was erected with concrete B 45. The use of the high–strength concrete proved to be very economically efficient due to reduced dimensions of structural elements and reduced demand for the further use of reinforced steel. Concrete mixture for Trianon building contained fly ash, superplasticizer and retarders. These concrete cube specimens taken for the compression tests showed that average compressive strength of B85 after 56 days was 112 MPa.
Altieri Spinelli Building (*Figure 6*), formerly called D3 building with its 24 storeys represents remarkable achievement in concrete technology in Europe; Altieri Spinelli Building is part of the complex of the parliament buildings in Brussels. High–strength concrete was used as a material for prefabricated columns in storeys that were reserved as garaging space. Target strength for these columns was 80 MPa, which was achieved by the addition of superplasticizers, reduced W/C ratio and the use of fly ash. Such concrete mixture and ability for prefabrication, resulted in accelerated construction and higher economic efficiency, smaller structural elements in this specific case of columns, left more free space than it would have if any other material was used. [6]

Figure 6. Altieri Spinelli Building, Brussels, Belgium [20]

Successful examples of high–rise buildings mentioned and described earlier and presented in summary in *Figure 7* are obvious evidences that the use of high–strength concrete is nowadays reality in construction worldwide.

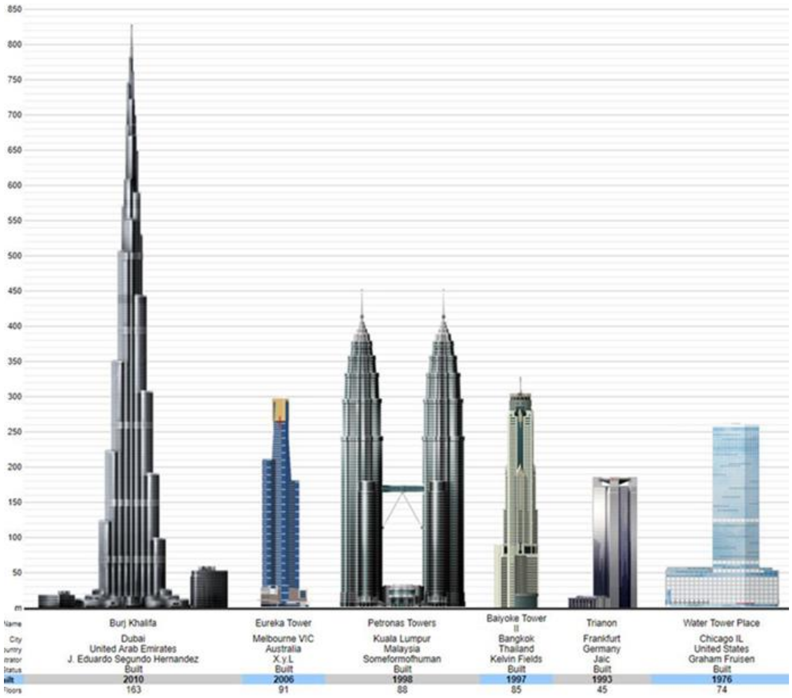

Figure 7. Summary of the Representative HSC High–Rises [21]

5. CONCLUSION

Whether focus on high–rise buildings up to 15– 24 storeys, or the super tall high–rise buildings that are few hundred of storeys high, high–strength concrete of different qualities is the unavoidable choice in search for structural material.

If technology development and economic efficiency opened up a gate to high–strength concrete towards wider market, high–rise buildings for sure enhanced benefits and abilities of high–strength concrete as commonly available structural material. Use of such environmental friendly, structurally safe and very resistant material enabled previously mentioned idea and concepts of vertical cities and vertical living.

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