Historical Development of Rammed Earth Construction and Its Use in Canada

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1 Introduction

Different processes of earth construction involve the dynamic compaction of soil to form a solid mass, and compaction of soil between formwork boards [1]. The latter involves the creation of vertical walls and is normally considered as rammed earth (RE) construction. RE construction entails compacting earth into a formwork. The formwork permits a RE wall to retain its structural integrity while drying. The earth composition can vary greatly but should have no organic content and sufficient binder between the grains of silt, sand, gravels, and small stones. RE construction involves repetitive placement of earth rammed with a manual or pneumatic rammer until the desired height of the wall is obtained. The building material may consist only of onsite natural earth, but lime or cement can be added to improve strength. Unstabilised rammed earth (URE) is based on the natural binding properties of clay particles. Stabilised rammed earth (SRE) supplements natural binding of clay particles with the addition of manufactured binders (cement, hydraulic or calcium lime) to increase compressive strength and durability with respect to water [2]. Historically, RE construction was applied over time in different regions of the world [3]. RE

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construction primarily was used where soil resources and climate were suitable, and where other building materials were unavailable in suitable quantities as well as at reasonable cost. Furthermore, RE construction could only be carried out where materials for formwork were present. With increased concern over sustainability during the past 50 years, RE construction received renewed attention. RE is considered sustainable due to its low embodied energy, long service life, and high recyclability [4]. New design techniques have allowed the spread of RE construction to colder and wetter climates. The purpose of this paper is to present an introduction to RE construction, its historical development, and its future as a sustainable building material. The next section of the paper contains a history of the technology in the world and in Canada. This is followed by a brief discussion of SIREWALL (a Canadian invention), with specific examples of its application in Canada, technical information concerning the characteristics and properties of both unstabilised RE and stabilised RE.

2 History of Re Construction

2.1 Global History

Earthen materials have been used since prehistoric times, and on five inhabited continents [5]. There are many forms of earth construction, including pit, cob, waddle and daub, abode (sun-baked) brick, compressed solid blocks, and RE [5–8]. Buildings made from soil are found in different forms, sometimes mixed with other traditional construction materials such as timber or stone, or with more modern inventions such as cement and steel [9]. RE is a very old construction technique that began probably thousands of years B.C. The term “rammed earth” has been used for different processes of dynamic soil compaction as applied to levelling ground, creating mounds, and creating vertical walls [1]. When the latter involves formwork boards which are later removed, it is often referred to as pisé or taipal. Few people realize the full extent of RE application historically, and the variety of techniques used [9]. The spatial distribution of RE technique is complex, appearing to spread over the world in several temporal waves triggered by differing needs [1]. The following section sheds light on the development of RE in some key parts of the world.

Development in Asia: RE construction has a long history in China [10] especially in the alluvial plains in northern China [1], where the soils had large clay content. About 3000–1900 BC, nomadic peoples of the late Neolithic Longshan culture began to form permanent settlements ringed with defensive earth mound walls. Evidence of the early use of formwork boards to produce RE walls comes from the walled Longshan settlement of Pingliangtai (Henan Province). RE was used in the construction of Shang cities, including walled compounds at Yanshi [11], Yuan and Hou [12]. The Qin dynasty (221 BC–206 BC), and the Han dynasty (206 BC–202 AD) constructed walls along the northern frontier of China with RE and adobe [13]. The Tang dynasty (618–907 AD) built cities (e.g., Xi'an) along the Silk Route with large RE walls as protection from Turkic tribes [1]. [14] argue that a 'true' RE technique first developed in China during the Three Kingdoms Period (221 AD to 581 AD) by the Hakka people (who originated in Henan and Shanxi provinces). When the Tang dynasty ended in upheaval (circa 900 AD) the Hakka migrated southward (to Fujian and Guangdong) and constructed fortified multi-storey Tulou round or square RE structures.

The Ming dynasty (1368–1644 AD) was a period of Chinese expansionism. Incursions along the northern border led to the upgrade and repair of the Great Wall, using fired brick and stone near Beijing and RE in the far west of China, such as Ningxia [1]. The city wall of Xian constructed during the Ming Dynasty was built using RE and later in 1559 enclosed with brick [13]. RE or adobe (sun-baked) bricks construction is common throughout Central Asia (Xinjiang, Quinghai) and in regions of the Himalayas (Tibet, Nepal, and Bhutan). Some evidence exists that RE construction has been used since ancient time in central Asia. [15] state that remnants of RE walls and houses found at Qinghai, Tsaidam between Tibet and Central Asia date from the Muomhong period (2000–500 BC).

18th and 19th Century Europe: In the last quarter of the eighteenth century, advocates of RE construction, including François Cointeraux in 1791, arose in France. Portions of Cointeraux four-volume set, titled *École d'Architecture Rurale*, were translated into German, Danish, Finnish, Russian, Italian, and English [16]. By the mid-1790s, British builders started to consider RE as an alternative to wood frame and cob construction. In *Communications of Board of Agriculture*, British architect Henry Holland provided a translated digest of Cointeraux's work on the erecting and removing wood framing, soil composition, and wall coverings, which greatly added credence to the RE pisé technique [17]. In eighteenth century Europe, RE began to be championed as a low-cost owner-builder construction technique due to concerns over deforestation due to timber construction. In Sweden, outbuildings of the Karlsborg Fortress in Stockholm were built from RE in 1842, and parts of the summer residence of the Queen of Norway was constructed in RE at Kongsvinger in 1890 [1]. During the Industrial Revolution, RE construction in Europe started to decline where Portland cement, iron and steel were available.

Expansion to the Americas and Australia: European colonists brought RE construction to North and South America, with earliest RE construction occurring in the mid-fifteenth century. The first RE in North America used a soil and sea-shell mix compacted in heavy formwork, found in St. Augustine, Florida and was built in 1556. RE was used in the Goiás and Minas Geras areas of Brazil. In São Paulo the cathedral of Taubaté was constructed from RE in 1645 [18–20] and the Church of Our Lady of the Rosary in 1720. RE use was widespread in São Paulo and the surrounding area during the 18th and early nineteenth century, until an 1850 flood resulted in a public campaign against the use of RE and the demolition of much of the RE architecture. In the United States, interest in RE developed during the Jefferson era [16], which was approximately 1800–1820. Having learned of Cointeraux's work, Thomas Jefferson built his home (Monticello, Virginia) using RE [1]. American lawyer Stephen Johnson used the works of British architect Henry Holland and his own experience with the material to promote RE, leading to a RE construction manual published in New Jersey, USA, in 1806 [16, 17]. Early in the nineteenth century, RE was used in constructing buildings on plantations in Virginia and South Carolina [16]. German immigrants constructed RE buildings in New York and Pennsylvania [21], and the farming areas in the American Midwest [16]. Chinese immigrants brought RE construction to California, as exemplified by a RE herb shop (The Chew Kee Store) built around 1850. However, with other materials becoming more available, interest in RE declined during the latter half of the nineteenth century. Renewed interest in RE arose during the periods of the depression period of the 1930s and the environmental movement of the 1970s [16, 22], followed later by an ongoing interest in RE as a sustainable building material.

During the 1860s and 1870s, RE construction became popular in the Riverina farming district of New South Wales [16]. During the latter half of the nineteenth century, RE construction also occurred in the wheat-growing areas of eastern and southern sections of Australia [16]. From the 1870s to the 1930s, Australia had many small building teams that specialized in pisé construction [16]. RE remains a well-established construction technique in Western Australia [1]. In 2002, Standards Australia published the *Australian Earth Building Handbook*, which outlines accepted good practice and recommended design guidelines [3].

Since 1950: RE was suggested as a solution to the housing and labour shortages following the two World Wars. However, its use became less when the post-war economy improved, and other materials again became affordable.

During the last 50 years, interest grew in RE as a sustainable construction material. RE has less embodied energy, i.e., the total amount of energy that goes into a product or service throughout its lifecycle, than traditional construction materials such as steel, fired clay brick, concretes, and cement blocks [23, 4]. Passive thermal construction using RE materials can also lower a building's operational energy requirements for heating and cooling, resulting in significant environmental and economic savings [23]. The renewed interest in RE as a sustainable building material led to several new research activities and the construction of several modern SRE buildings. The traditional concept of RE construction still applies to structures being built in North America today, but there are substantial differences as were noted earlier between URE and SRE. As many jurisdictions do not have specific design codes or standards with respect to RE construction, masonry and concrete building codes are often used as guidance by licensed structural engineers in designing RE structures [24]. RE construction is often considered unconventional construction, and this often increases the regulatory approval with respect to planning approvals and building permits.

Modern RE began simultaneously in the early 1980s in California and Western Australia where formwork was invented specific for ramming earth/10% cement mixtures. Also, in the early 1980s, France charted a different course with the intent of not using any cement. This approach was embraced in the early 2000s by the Swiss and the Germans. Meror Krayenhoff (co-author of this paper) saw that the French approach would not work in Canada due to lack of strength, and that the Californian/Australian approach would not work due to lack of insulation. Research resulted in SIREWALL (Structural Insulated Rammed Earth). It also resulted in many global firsts of which Canadians should be proud: insulating RE, making RE as strong as concrete, using iron oxides in the mix for colour, and incorporating carvings in the formwork, recessed plugs, stump windows, and gang forms. Now there are many RE companies in Canada using SIREWALL technology.

3 Re in Canada

There are several examples of RE construction in Canada, the first known dating back to 1838. A select few examples of RE construction in Canada are highlighted below.

With construction starting in 1838, St. Thomas Anglican Church in Shanty Bay, Ontario, is one of the early Canadian examples of RE construction [25]. Wet clay and straw were compacted into forms until dry and then covered with siding or plaster to protect from the elements. The church, a provincial heritage site, demonstrates the longevity of RE as a building material for use in Canada [25].

Structural Insulated RE (referred to as SIREWALL in this paper) was pioneered in the early 1990s by a co-author of this paper (Meror Krayenhoff) on Salt Spring Island, B.C. Cement (9%) and possibly clay are the binders, and compaction is achieved with specific pneumatic and hand tampers, yielding 20–50 MPa. The greater strength is achieved through careful mix design, an integral hydrophobic admixture, and sometimes pozzolans. The addition of insulation makes RE useful in a much broader climatic context. SIREWALL is a Canadian invention with the strength of concrete while using a fraction of the cement used in concrete.

Benefits of SIREWALL include: (a) Strength—SIREWALL has been built to 30 m in height, and been used for a 15 m lintel, (b) Health—contains no Red List chemicals, hence no outgassing, c) Insulation—static R-value of R33, which can/has been increased to R66 when desired. Dynamic (mass enhanced) R-value is 1.5 to 2.25 × the static R-value, (d) Durability—stick-frame homes last 30–40 years before major repairs or demo, whereas a SIREWALL home can last for hundreds of years, (e) Maintenance—extremely low maintenance. Pressure wash every 5–10 yrs or as necessary, (f) Climate Change Ready—impervious to fires, flooding, high winds, extreme temperatures, and insects, (g) Cradle to Cradle—the materials that make up the SIREWALL can be reused for the same purpose, hence ending the debilitating resource extraction/landfill cycle, (h) Passive Solar friendly—insulated mass is the best imaginable partner to passive solar design, (i) Hygric Buffering—similar to the thermal flywheel effect, SIREWALL has a humidity flywheel effect, which stabilizes the interior humidity to a tight range, typically between 40 and 55% RH. This is important to eliminate mold and create an inhospitable environment to viruses. Examples of RE in Canada are shown in Figs. 1, 2, 3. Figure 1 is that of a wall constructed in Salt Spring Island in 1992. Figure 2 is an example of a structure constructed at the Edmonton Valley Zoo in 2012, and Fig. 3 is an example of a commercial use of RE at the Nk'Mip Desert Cultural Center in Osoyoos, B.C. There

Fig. 1 RE constructed in 1992 on Salt Spring Island, BC (Courtesy: M. Krayenhoff)

Fig. 2 RE constructed in 2012 in Edmonton, AB (Courtesy: M. Krayenhoff)

are some aspects of SIREWALL that still need to be improved, these include: (a) It uses cement which has high embodied energy, (b) It is labor intensive and requires technical expertise. (c) It is machinery intensive, and (d) It can only be built on site and is therefore vulnerable to the vagaries of climate.

Other examples of RE in Canada include one constructed in 2008, the First Peoples House, located at the University of Victoria in B.C. This structure has two RE walls that exemplify the use of SRE as a modern construction material [26]. Both walls are 500 mm thick, and exterior-interior portions of the walls have a 100-mm thick central cavity for insulation with internal steel reinforcement for added strength [26]. Non-destructive Testing (NDT) of the walls after seven years of exposure to natural

Fig. 3 Nk'Mip Desert Cultural Center, Osoyoos, BC (Courtesy: M. Krayenhoff)

weathering in a wet climate is discussed in [26]. They noted that the effects of surface weathering were indistinguishable from the natural texture of RE.

Currently, RE builders in Canada use a double RE wall system closed over on the ends with an interior layer of insulation. The RE works in conjunction with the insulation to reduce heat flow across the wall. [27] describes the first insulated RE house in Ontario. The 350 m^2 house situated in Castleton, Ontario, has a 0.45 m wide wall consisting of inner and outer wythes (vertical wall sections) of 0.15 m of RE sandwiching 0.15 m thick insulation. Structural integrity is ensured with a 0.6 m rebar spacing, which minimises cracking risk in each wythe and connects the two wythes [27]. [27] also discusses the design and construction considerations with respect to the Castleton house. During construction, insulation was placed in the centre of the form and the earth mix placed by mechanical and hand shovelling and rammed with pneumatic sand tampers and finished with hand tampers. The minimum amount of water sufficient to permit thorough mixing was added, to limit the drying period and the potential for cracking [27]. The mix for the Castleton project, based on soils from a local quarry, yielded 16.8 MPa based on cylinder compression tests [27].

Krahn and Dick [28] presents two case studies of SRE construction in Canada (the Allen and Smyth-Allcott residences), with a discussion of structural design considerations and regulatory processes, requirements, and constraints. In Canada, design standards published by the Canadian Standards Association for common building materials such as concrete, masonry, steel and wood and the National Building Code refers to these design standards as acceptable tools for meeting relevant objectives and functional statements. In Canada, materials without specific design standards, such as RE, pose a challenge for regulators lacking experience with the material. Despite considerable international experience and research on RE, Canadian engineers have difficulty defending RE designs within current building codes [28]. The Allen residence, located near the town of Huntsville in the Muskoka region of Ontario, was completed in 2012. Engineering design followed some aspects of CSA A23.3–04 "Design of Concrete Structures", primarily for axial-bending analysis of wall sections, beam design, and guidance on reinforcing steel detailing [28]. Design compressive strength value was based on preconstruction testing of several mix designs. Freeze–thaw testing was undertaken based on the CSA A23.2 concrete materials standard. Using a compressive strength of 15 MPa, the reinforcement requirements of a typical wall section (two 150 mm interconnected wythes of 5.5 m height separated by 150 mm of rigid insulation) was 10 M vertical rebar at 600 mm centres, and 10 M horizontal rebar at 600 mm centres, installed in the centre of each wythe. An HDPE geo-grid, embedded a minimum of 100 mm on either side of the insulation, continuously along the wall at 600 mm intervals was used to laterally brace the 150 mm wall segments, thereby reducing the slenderness ratio of the wall [28]. The New Zealand Earth Building Standard NZS 4297 lists geogrid as an acceptable shear reinforcement material for standard (raw) RE wall systems [29]. Thermal performance was a primary concern in this project's design, and reduction of thermal bridging across the inter-wythe insulation was an important objective [28]. At the top of the wall, where roof loads come to bear, steel inter-wythe connectors were specified to avoid potential creep effects in the HDPE geogrid. This allowed the inter-wythe insulation to extend up past the top of the wall assembly and connect to the attic insulation, reducing thermal bridging and providing a continuous air seal. At the base of the wall, under the interior SRE wythe, two rows of 150 mm wide high strength expanded foam glass block were installed to provide thermal separation from the foundation. The plan examination department in the town of Huntsville accepted the design as code conforming under part 4 of the Ontario Building Code with the condition that the RE construction be inspected by the design engineer [28].

The Smyth-Allcott residence, located just north of Kemptville, Ontario, has a typical wall cross-section of a 200 mm wide interior SRE wythe, an interior 150 mm of insulating material, a 150 mm wide exterior SRE wall segment, and vertical rebar with 600 mm inter-wythe connectors [28]. Due to the presence of clay in the SRE mix, and a proposed design compressive strength of 15 MPa, building plan examiners would not accept the use of the CSA A23.3 concrete design standard, which does not allow particles below 80 μm in diameter and requires a minimum compressive strength of 25 MPa for reinforced concrete in bearing locations. Therefore, the CSA A304.1 masonry design standard was used which allowed for lower minimum compressive strengths and more emphasis on overall wall geometry rather than focussing primarily on reinforcement [28]. Pre-construction compressive strength testing resulted in a design compressive strength of 10.5 MPa. Because there is no published standard for engineering design of RE in Canada, and no corresponding material standard, plan examiners would not allow the exterior SRE wythe to be considered a structural component but a non-structural veneer. This meant that the interior wythe had to be sufficient to handle all the structural loading [28]. To resist the in-plane shear loads, 15 M rebar was required vertically on 600 mm centres with horizontal reinforcement of 10 M rebar also at 600 mm spacing and an extra run of horizontal rebar was requested at the top of the wall to reinforce the SRE near point and line load locations [28]. From a regulatory standpoint, using a masonry design standard in engineering design has advantages, but masonry's characteristics are not directly comparable to those exhibited by SRE. Other design standards (such as concrete engineering) may be more appropriate for some structural components of SRE construction [28].

4 Re Properties and Characteristics

To provide some background to readers, this section presents introductory information on RE properties and characteristics. It should be noted that the mix design of SIREWALL is distinctly different from that of other versions of RE and details provided below are that for the older versions of RE only. Additional information can be found in the technical literature.

4.1 Material Properties

RE has material properties that include the grading of soil, clay mineralogical composition, plasticity, dry density, optimum moisture content, suction, and anisotropy [2]. Void ratio and particle size distribution (PSD) helps define the mechanical behavior of the earth material. When the void ratio is low, the contact between soil particles is higher, resulting in greater strength and weathering resistance [3]. Therefore, proper compaction work during the execution of RE components (wall, column, etc.) is important [2]. Soils for engineering use are classified according to the size proportion of their main elements: gravel, sand, silt, and clay. The minimum and maximum percentages of the main soil elements that should be used for URE are 20 and 35% for clay and silt, and 50 and 75% for sand, respectively [3]. The cohesive forces observed inside the voids of a soil act differently according to the PSD and the type of soil. Cohesion in a sandy soil is primarily provided by capillary forces between particles whereas, cohesion in a clayey soil is provided not only by capillary forces but also attraction forces of clay particles [30]. Between layers of clay minerals, a primarily electrostatic cohesive force exists, which is then amplified by Van der Waals attraction. Providing clay content is enough to ensure the binding phenomenon takes place, the activity of clays may have a greater effect on the mechanical behavior of RE than the amount of clay.

Suction is a physical property of unsaturated soils that describes the potential with which a given soil at given water content adsorbs and retains pore water. Total soil suction consists of a matrix component associated with capillary action between particles with the mechanism of particle surface hydration, and an osmotic component associated with dissolved solutes in the pore water. [31] and 30] confirmed that suction is a source of strength in URE, including increased shear strength. In addition to suction, other features such as the densification and possible particle interlock promoted by the ramming process during the layers' construction can increase strength [31].

4.2 Mechanical Properties

Mechanical properties include elastic parameters, compressive strength, tensile strength, shear strength, flexural (bending) strength, and durability. When used in combination with steel reinforcement, the bond between the rebar and the compacted soil also becomes of interest. A wide variability of mechanical properties is found in literature due to the differences in earth properties, sample size and geometry, and testing methods and conditions. Values for the Young's modulus generally range between 60 and 750 MPa [32] for URE. The Young's modulus measured parallel to the layers was about 25% higher than the one measured in the perpendicular direction [33]. Values for the compressive strength of URE obtained by laboratory tests can vary from 0.5 to 4.0 MPa. However, some codes specify compressive strengths between 0.4 and 0.7 MPa [3]. Values of compressive strength parallel to layers are slightly higher (about 10%) than compressive strength perpendicular to layers [33]. A small increase of water content (or increase of relative humidity) is followed by a huge reduction of both compressive strength and elasticity modulus. URE material is very weak in tension and therefore URE elements should not be designed for pure tension [3]. Using tension tests (direct method) and splitting tests (indirect method), [34] found that the two URE samples and one SRE sample reached a range of 5.0–12.5% and 15–20% of the corresponding unconfined compressive strengths, respectively. Bui et al. [7] proposed that shear strength should be taken as 10% of the unconfined compressive strength (before considering safety factors). The use of cement as a binder can increase the compressive strength. For instance, a study by [35] reported a compressive strength of 18 MPa. Other studies (presented in Sect. 3) report significantly higher compressive strengths when cement is used as a binder material.

4.3 Durability

In addition to strength, durability is another important consideration with respect to RE walls. Durability of RE is driven by mechanisms by which water can enter a structure, such as rainfall impact on a wall surface, water flowing down the wall, flow through bordering soil, capillary action from the ground, and ponding in exposed openings [36]. Miniature problems caused by water initially may result in structural issues that allow water ingress in a structure, thus causing further damage [36]. Bui et al. [37] presents an extensive study on the durability of stabilised and unstabilised RE walls exposed for 20 years to natural conditions in France. The walls were protected from the capillary rise from the foundation, but it was exposed to precipitation averaging 1000 mm per annum. The mean erosion depth observed was 2 mm (0.5% of the wall thickness) for the stabilised walls and about 6.4 mm (1.6% of the wall thickness) for the unstabilised walls. RE walls also deteriorate due to plant growth, wind action, and animal or human action [16]. Plants such as lichens, mosses, fungi, and algae break down the interlocking bonding structure of the earth components on the surface of the wall, and cause the chemical structures of the clay particles in the soil to change. This results in surface erosion as the compromised powder-like soil is sloughed by wind or rain [16]. A study conducted by Khan et al. (2019) investigated the effect of accelerated wetting and drying cycles on mechanical properties of SRE. It was found that the strength of RE material was enhanced by 23% when 15% of the cement quantity was replaced with supplementary additives, i.e., 7.5% Metakaolin and 7.5% fly ash, upon exposure to wet-dry cycle as compared to the same sample when exposed to ambient conditions. Some of the SRE construction utilize waterproofing admixtures mixed into the soil–cement mixture and some use a sealant on the surface to reduce the permeability of the walls.

4.4 Seismic Response

The seismic action on a building can be considered equal to an equivalent static force applied to the base of the structure, which depends on the building fundamental period and the damping ratio of the material constituting the structure. Bui et al. [38] measured on site first natural periods obtained between 4.1 and 12.1 Hz, and determined damping ratios between 2.5 and 4% for residential RE structures in the Rhone–Alpine region, France. The damping ratio of investigated structures differs as the earth material and water content is different for each house, and the global damping of the RE structure is affected by the configuration, and connections and openings within the building frame [38].

4.5 Thermal Properties

As a dense material, RE has high thermal mass, the passive ability to absorb and retain heat energy, thereby decreasing large temperature variations and reducing peak energy demand for heating and cooling [23]. The moderating effect of thermal mass is an important property in climates where temperatures fluctuate greatly diurnally and seasonally. As a dense material, RE, depending upon its constituents and compaction, often presents a high thermal conductivity comparable to concrete and other dense building materials and thus, a poorer insulation ability. However, the effects of high thermal conductivity on the thermal performance of a RE wall is mitigated by the high thermal mass [23]. [4] investigated the thermal behaviour of URE walls under two different climatic conditions (arid and Mediterranean) using thermocouples to obtain temperature profiles in the walls during the summer and winter of 2013. They found that RE walls decreased the thermal amplitude from outside to inside temperatures resulting in constant temperatures in the inner surface of southern walls, and this decrease was greater for thicker walls. It should be noted that the discussion above is for URE and systems like SIREWALL are insulated and offer superior thermal performance.

5 Concluding Remarks

Three distinct versions of RE are: (i) historical unutilised RE (URE), (ii) Stabilised RE (SRE) and (iii) Structural Insulated RE. The mechanical properties can vary greatly depending upon the version of RE used. Historically, URE has been used for several decades and continues to be a sustainable construction material. However, the utilization of URE as a construction material is hampered by issues such as low compressive strength, high permeability, and a labour-intensive construction process. However, the advent of modern cement-stabilized RE (SRE) and structural insulated RE has enhanced the feasibility of this ancient construction technology for various mainstream applications.

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