Enhancing Rammed Earth's Accessibility Through Novel Tectonic Machines: Developing and Testing a Rotational Tamper

Marcus Shaffer[1[0000-0003-0361-1141]]

[1]Penn State Architecture, University Park, USA

ABSTRACT: In the realm of accessible building technologies, rammed earth construction is a low-skilled, low-cost process of making architecture that commonly employs material found on site. This ancient construction process, where a loose earthen material mix in formwork is compacted with simple tooling, results in walls that are sustainable, healthy for inhabitants, and high-performance. Rammed earth walls offer functional compressive strength, filter air, capture and release heat, transpire moisture, become more durable with age, and are resistant to fire and infestation.

While anyone can skill-up to make rammed earth, the basic tooling and intensive labor involved can significantly tax and/or harm a builder's body. This form of *inaccessibility* can be off-putting to would-be earth builders, people who may not possess or who cannot afford the requisite calorie-intensive physicality to construct with rammed earth. The research detailed in this paper starts with the observation that rammed earth construction is associated with a technological evolution filled with gaps. In the current spectrum of rammed earth tooling/machinery there is significant space for machine development – new tooling/machines that operate between hand-tamping (low tech), and industrial-scale robotics and/or rammed earth "printing" (high tech).

With the goal of making rammed earth architecture more accessible by specifically addressing the requisite physical labor, a series of prototypical machines – Rotational Tampers – were developed and fabricated at 1:1 scale. These machines were tested in producing rammed earth walls and/or test samples for compaction, while monitoring the machine-user's heart rate as means of measuring expended energy in relation to tamping. In developing the machines, the researcher prioritizes *simplifying* the Rotational Tamper (easy to fabricate, assemble, and maintain), its *operation* (easy to set up, intuitive to operate, and easy to disassemble), and its *effectiveness* (producing quality rammed earth with less effort). Ultimately, the resultant Rotational Tamper(s) will be freely available as open-source plans/instructions.

KEYWORDS: Rotational Tamper, machine development, accessible rammed earth, low-calorie rammed earth, Tectonic Machines

INTRODUCTION

A common statistic associated with earth-based architecture is that approximately half of the world's population lives and/or works in buildings made of earth – many of these buildings are *self-built*, which implies a process done without the participation of an architect or professional contractors. Within the profession of architecture however, rammed earth has been gaining attention over the past decade thanks in part to the experimentations, constructions, publications, and consulting of Martin Rauch – who is essentially attempting to conventionalize or mainstream (un-stabilized) rammed earth as a building material (Rauch 2023). Additionally, well-known architects such as Renzo Piano (2020) and Herzog & de Meuron (2014) have used rammed earth in constructing buildings that have been widely published. While the benefits of using earth as a building material include good performance in measures related to sustainability, structure, human health, and ecology, there are also considerable problems to address. A partial (and paraphrased) listing based on one found in *Earth Construction: Lessons from the Past for Future Eco-efficient Construction* (Pacheco-Torgai & Jalali 2011) includes the following issues:

1. Lower durability of earth compared to conventional construction materials
2. Earth construction is labor intensive
3. Earthen constructions perform poorly in earthquakes
4. Earth budlings are structurally limited
5. Earth buildings might be considered high maintenance
6. Professionals make less money on earth-based projects
7. Special skills are needed for plastering (plaster prevents decay)
8. Earth is considered a non-standardized material re: building codes
9. Wall thickness is greater than other means of construction

The research presented in this paper addresses rammed earth's intensive labor. In the process of constructing with rammed earth, the requisite labor might be loosely categorized into three groupings: 1) earth material excavation and mix preparation, 2) formwork fabrication and/or formwork system assembly and disassembly, and 3) placing and tamping the earth mixture in the formwork. In this research, the author targets rammed earth's labor intensiveness, specifically in relation to *tamping*, through a gap in the technological development of tooling commonly used in rammed earth construction (Figure 1).

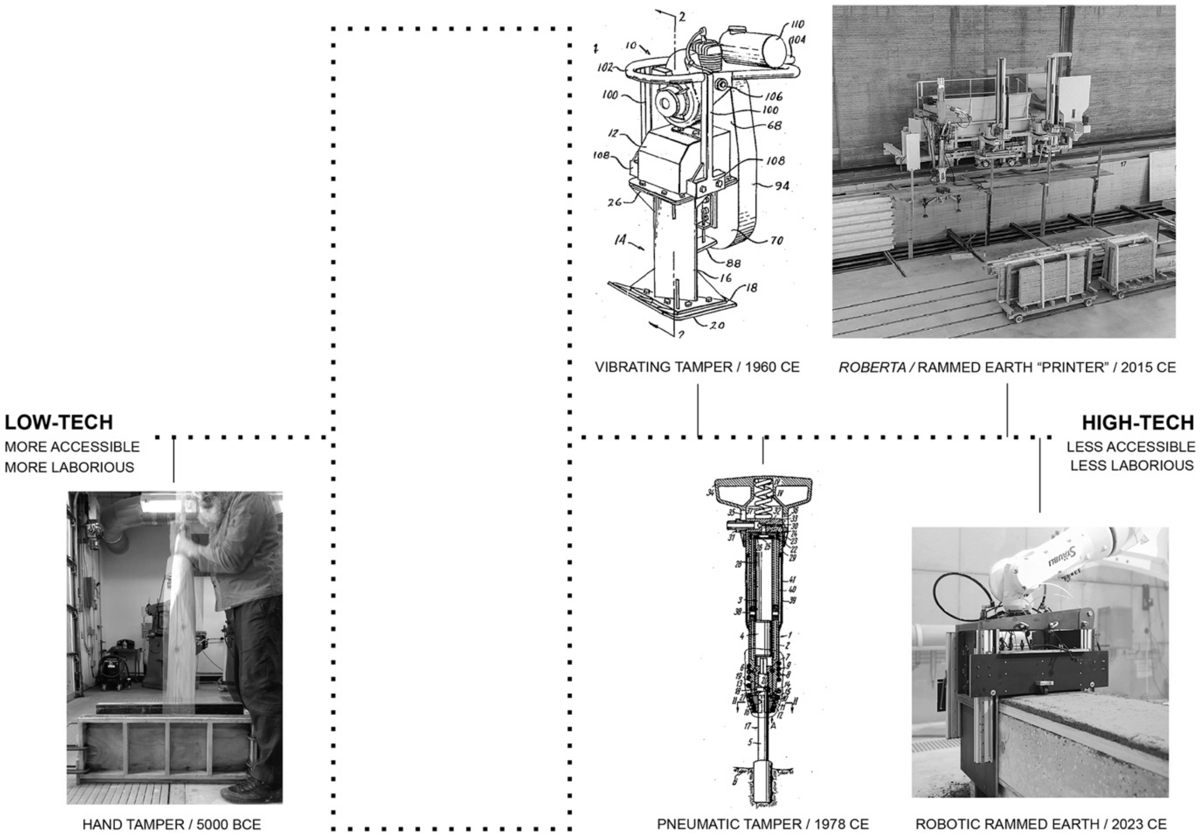

Figure 1*:* A considerable technological gap exists between the manual tamper as a low-tech tool (L), and high-tech mechanized means of ramming earth (R). This is a space for rammed earth technology development. Source: (Author 2023). Photographs at right used with permission: © Hanno Mackowitz & © Joschua Gosslar, Institute of Structural Design, TU Braunschweig. Patent drawings are opensource, USPTO. Hand tamper image, Author 2024.

This work begins with a hypothesis that simple machines reliant on body-activated mechanical advantage – rather than machines that are motor and fuel dependent – can be developed to significantly displace the labor burden associated with rammed earth tamping. Rammed earth builders today have three tooling options to employ when tamping, each one associated with different degrees of labor intensity: the *hand tamper* (essentially the same tooling developed in China 7,000+ years ago), *pneumatic tampers* driven by compressed air generators (gas or electric powered), and *modified industrial machinery* for manufacturing prefab rammed earth (e.g., manufacturing robots with special end effectors, or over-scaled earth *printers*). Of these options, hand tamping is the most accessible and the most labor intensive in that it requires the user to repeatedly lift and drop (or thrust) a weighted instrument as means to compact loose earth in a form. In building a wall, this action is repeated thousands of times, and the physical stress on builders can tip *laboring* into *suffering*. Pneumatic tamping is less accessible and less laborious but can cause serious vibration-related injuries in tool handling. Online occupational governance in California (and the UK warns of the potential harm caused by the *whole-body vibration* and/or *hand and arm vibration* associated with machines that transmit violent impact-compaction into the human body.[1] Pneumatic tamping also presents accessibility issues related to economics, requiring the purchase or rental of a tamping machine, air compressor, and onsite fuel or electric power. Additionally, these machines are quite heavy. Compared with these two options, factory-based industrial tamping machinery is significantly *not* accessible today. Capital, technology, heavy machinery, fuel, specialized labor, and transportation costs are all significant barriers to making this technology commonly accessible. One could add that coding/programing skills also represent a form of inaccessibility with these later technologies, as the machines are code-driven. In terms of labor, one can see specialized (skilled) labor and a high degree of mechanization/automation in high-tech rammed earth processes such as Lehm Ton Erd Baukunst's *Roberta* (https://www.youtube.com/watch?v=z5M7KG5EnB0), and in the manufacturing robot-based work being developed by Joschua Gosslar at TU Braunschweig (https://www.youtube.com/watch?v=X0v94Ejif_Q).

1.0 FULL SCALE EXPERIMENTS IN SIMPLE MECHANICAL COMPACTION

The work presented in this paper represents the development phase of research that investigates the use of simple machines to make rammed earth construction more accessible/less laborious. Research progresses along *proto-*

typological research methods proposed by Heisel and Hebel (2019), where “a full-scale application, that is an experiment and proof in itself” is used to evolve Rotational Tamping. In *Prototyping for Architects* (Burry & Burry 2016), the authors write, “Whether the prototype actually works or not is not the issue; prototyping is the *revelatory process* through which a designer gains insight into how well their experiment is proceeding. Failure offers important information which… increases the chances of a more successful outcome.” In this research, the development of Rotational Tamping proceeds as iterative full-scale machine fabrications that are tested and measured, with research aims/goals informed by what succeeds and what fails.

The development of the Rotational Tamper began with a very simple mechanical idea – a heavy wheel. The earliest iteration of the Roto-tamper existed as a very heavy cast concrete wheel (400 kg) that was rolled into a braced formwork and then rolled back and forth while earth mixture was placed in the form cavity from above. The resultant earth was so overly compacted that it could be picked up as a beam (Bick 2016). Despite the effect of this concrete wheel as a hyper-compactor, two critical issues emerged during this preliminary test: 1) at the termination of the tamping phase, builders should not have to remove a very heavy (dangerous) object overhead from the formwork, and 2) the round shape of the wheel could not compact flat layers of earth at the termination of the formwork. At the ends of the constructed wall, the earth was not compacted, which meant that already vulnerable rammed earth corners and edges needed to be tamped by hand. Two additional iterations of the heavy wheel (RT-Zero Series B and C) where developed and tested (Figure 2); a concrete wheel in five parts (RT-ZSB) which allowed the heavy wheel to be disassembled in the form post-tamping, and a wheel made of an industrial drum (RT-ZSC) that could be filled with gravel before tamping, and then be emptied for removal from the form post-tamping. While these further iterations significantly addressed the issue of removing a heavy wheel from overhead in the form post-tamping, all three RT-Zero Series devices required significant conventional tamping at the ends of the resultant wall, which also impacts total labor requirements.

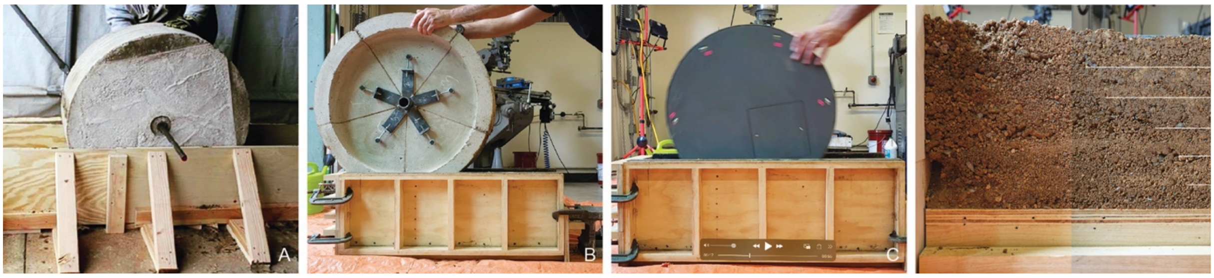

Figure 2: Three wheels/rollers foundational to Rotational Tamper development: A) 400 kg concrete wheel, B) a 180 kg concrete wheel that can be disassembled into five manageable parts, and C) a 77 kg wheel made of a steel drum and filled with gravel. While B and C solved the issue of removing a heavy tool from the formwork post-tamping, all three wheels were not able to compact earth at the ends of the formwork – a seen in the image on the right. Source: (Author 2023)

From these first experiments the researcher determined to move forward with something that rolled, as the concrete wheels had been relatively easy to move in the form. Other criteria that emerged from the concrete wheel test included 1) the idea of a “wheel” that was made of parts, one that could be assembled to tamp and then be taken apart atop a completed rammed earth wall, and 2) a wheel that included “stepping tamper plates” that could be manipulated to compact where parallel form side boards met the form bulkhead – resulting in compaction along the total length of the formwork. With these criteria articulated, the next iteration of the Roto-tamper (RT-01) was further informed by several outmoded pieces of technology (Figure 3): the *Dreadnaught Wheel* (1840+), a *Wheel for Road Engines* (1890) and the *Diplock Wheel* (patented 1900).

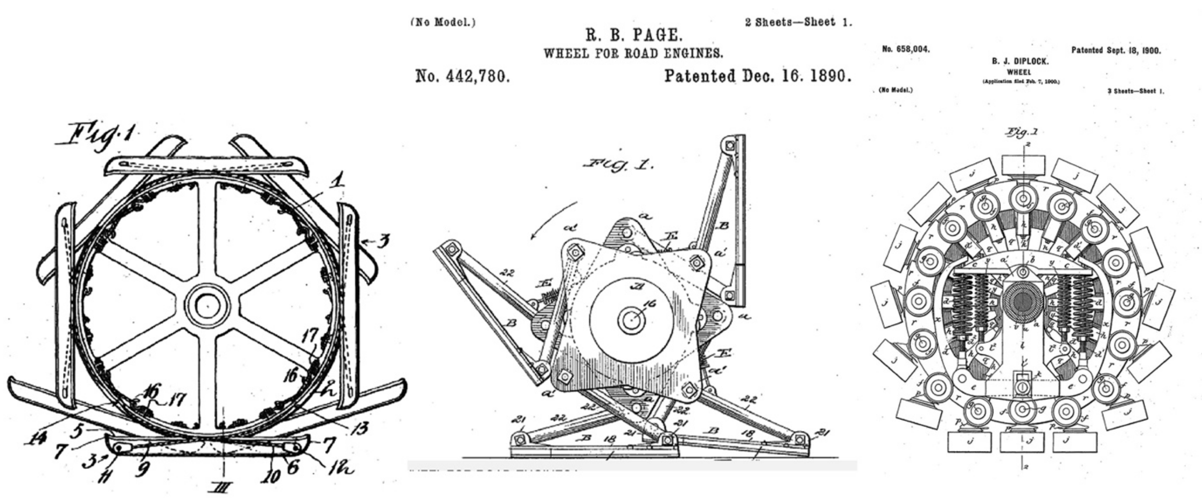

Figure 3: The *Dreadnaught Wheel* (L), *Wheel for Road Engines* (1890), and the *Diplock Wheel* (1900) are just a few outmoded technological means of moving heavy loads over unstable soil before caterpillar tracks became prominent in the 1900s. While not developed specifically to compact earth, these “walking wheels” as rolling/stepping compactors inspired the development of Roto-tampers 1 & 2. Source: (UK Patent Office and US Patent and Trademark Office).

1.1 Roto-Tamper 01

The development of the first Rotational Tamper (Roto-Tamper 01 or RT-01) took shape as a straight-forward eight-spoked wheel with large pivoting tamper plates on the end of each spoke. The spoke wheel was constructed using eight identical steel box tubes (7.7 cm x 7.7 cm). Rather than create complexity in fabricating the spoked wheel with angle-ended spokes as seen in the wooden prototype of RT-01 (Figure 4), the steel spokes are cut blunt-ended, and arrested in their angled positions with star-shaped plates. These plates were fabricated using a cnc plasma cutter, as were the triangular brackets of the tamper plates. In the production phase of RT-01 the researcher began to prioritize simplifying the design of the machine, use of common or stock pieces of steel, and the elimination of skilled fabrication methods (RT-02 would try to stay in the realm of metal cutting with saws or shears, MIG welding, cold work, and drilling holes). In future iterations, the use of the cnc plasma cutter as a fabrication tool would be eliminated. Fabricating RT-01 also required adding noise dampeners to each spoke, which eliminated a loud mechanical *CLANK!* caused by the tamper plates crashing into the spokes as the machine rotated (they also limited the swing of the tamper plate on the end of the spoke). Finally, to start, RT-01 had bearings positioned at the center of the spoke wheel – a feature carried over from the wheels that preceded this design. In RT-01, the difference between a rolling tamper, and a tamper that *steps* became clear… and the bearings at the center of RT-01 proved useless as RT-01 acted like a series of sequential levers rather than a wheel (RT-01's center moves up and forward in a rotating triangular motion as the machine is pushed through the form).

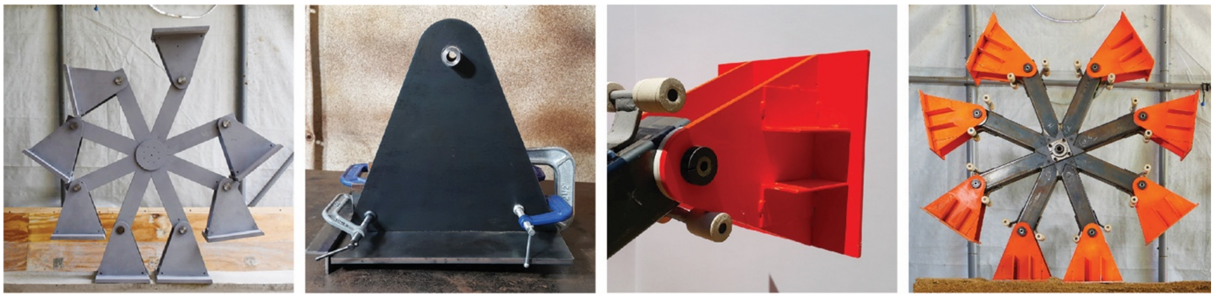

Figure 4: Roto-Tamper 01 evolved from a wooden prototype used to determine the overall dimensions of the various parts (L) to a steel machine that was employed to make a rammed earth wall test (R). Through this process, fabrication technologies were assessed for accessibility, and unforeseen components – such as noise dampeners – were designed on the fly. RT-01 did not actually roll, it stepped. Source: (Author 2023)

When the fabrication of RT-01 was complete, other unforeseen problems associated with Rotational Tamping emerged, specifically with the formwork. It is not uncommon for the sideboards of rammed earth formwork systems to be tensioned *through* the wall with tie rods, as the downward thrust of tamping can force the sideboards to push outward or bulge. In Rotational Tamping, the space of the formwork must be kept clear to allow for the back-and-forth passage of the machine. The Rotational Tamper also needs "overhang" space at the ends of the formwork cavity so that a tamper plate can act on material at the ends of the form. This necessitates formwork that can be tensioned from outside of the formwork cavity. The Rotational Tamping formwork cavity – as both the space that anticipates the rammed earth wall *and* a machine space, also necessitates that the machine user/wall builder is positioned outside of the form (it is not uncommon for rammed earth builders to stand inside formwork as they tamp the earthen material). In the realm of RT-01 formwork (Figure 5), one other unforeseen problem required immediate adjustment. The tamping plates of RT-01 (25 cm x 25 cm X .635 cm) were cut square, and their dimensions nearly match the width of the rammed earth wall anticipated in construction (+/- .635 cm). As soon as RT-01 began to operate inside the exterior-tensioned formwork, the downward step of the steel tamping plates began to destroy the top edge of the formwork sideboards. The immediate remedy was to dismantle the formwork sideboards and cut away the top inside edge at 30°. As of this writing, the development of appropriate Rotational Tamping formwork still requires attention.

In constructing the first rammed earth wall with a Rotational Tamper, the researcher made a preliminary wall that employed climbing formwork (a small vertical section of formwork that moves up with the tamping). This process was quickly abandoned in favor of a full-wall formwork as to better support the externally tensioned formwork on a concrete footer, and to contain any unforeseen effects of vibration caused by the stepping machine while making the first wall test. The second attempt at RT-01 Wall proceeded without further incident, with the machine user (a 53-year-old male with conventional rammed earth construction experience) monitored for heart rate (HR) specifically while tamping (heart rate results appear in section 2.1). While constructing RT-01 Wall, it was observed that the machine operator should use the uppermost tamping plates as "handles" to step the machine back and forth through the form, and to "jog" the machine (a micro movement) when tamping at the ends of the form. It was observed that a person using the spoke as a control lever could have his/her arm dragged into the form, where it could be caught between the top edge of the formwork and the following spoke (carried by momentum). Keeping hands on top of the machine (using tamping plates as push points) became a safe operation requirement and initiated a revision to the wheel component in RT-02. When RT-01 Wall (304.8 cm x 26 cm x 198 cm) was completed, RT-01 was dismantled from atop the form/wall, and each piece was passed to the ground. Dismantling the machine took five minutes (Figure 6). Each RT-01 tamping plate weighed 7.7 kg, the spoke wheel weighed 29 kg, and tamping plate hardware sets (one axle, two shaft collars) weighed .5 kg.

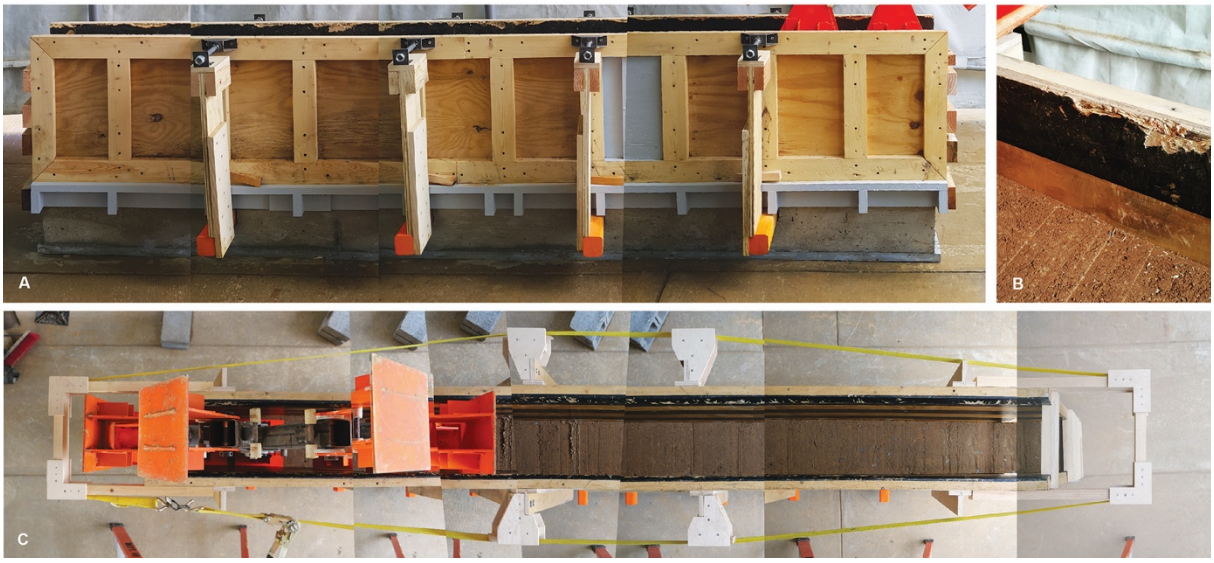

Figure 5: A novel machine for ramming earth requires formwork that is also somewhat atypical. Rotational Tamping formwork required external means of tensioning the sideboards of the formwork. At the lower level of the form this was achieved with mechanical adjusters that put inward pressure on the form (A). As the rammed earth wall grew and more layers of formwork were added, the top layers of the formwork were tensioned with heavy duty ratchet straps and wedges, as seen in the plan view (C). RT-01 also shredded the top edge of the formwork (B). Cutting it away at an angle allowed the square steel tramping plates to ease into the form rather than collide with the top edge as they entered the form cavity. Source: (Author 2023)

1.2 Roto-Tamper 02

At the start of the discussion of Roto-Tamper 02 it is important here to emphasize the researcher's desire to simplify the machine. The design and fabrication of RT-02 would be kept within a realm of common/simple metal working skills and common metal parts/hardware employment. Engineer Raul Ramírez's CINVA Ram (1952-1956) appears here in the research as a model/ideal simple machine that eased the physicality/labor burden of making earthen block in contrast to blocks laboriously hand-pressed in wooden forms (Figure 7).

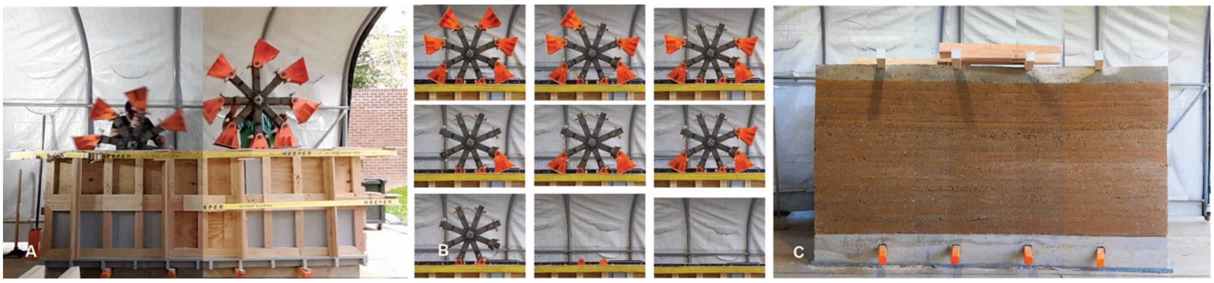

Figure 6: (A) Composite images from video show RT-01 Wall being constructed, the machine rising out of the formwork as the earth is tamped in layers. In both stills, the machine operator is using the spokes as levers/operating handles – this was determined to be an operational hazard (and design flaw) in RT-01. (B) RT-01 is easily dismantled when the wall is complete. The weight of each part becomes a key factor in further machine development, as overall weight effects compaction capacity, while part weight determines who can dismantle the machine safely. (C) RT-01 Wall completed. Source: (Author 2023)

The CINVA Ram and other more simplified manual block presses are designed around an ethos of *easy to manufacture, easy to maintain and repair.* The accessibility component that is at the essence of the Rotational Tamper should also include *fabrication skills access*, *manufacturing technology access*, and a certain obviousness in assembly/repair that translates into *accessible maintenance*. Additionally, there is a tectonic thinking/skills-transmission component built into the CINVA-Ram that also influences the Rotational Tampers. These machines – *Tectonic Machines* – enable builders with no-to-little skill to create intelligent architectural components, blocks, walls, etc., through direct engagement with the tooling. As a novice builder receives blocks of a certain thickness and dimension from the compaction chamber of the CINVA-Ram, block dimensions that have been deemed easy to handle, appropriate in size to the material, and appropriate in their material volume to support wall-building, so the tamping plate dimensions of the Roto-tampers, their obvious compaction capabilities, and linear movement represent a prescription of sorts – in machine form – for linear rammed earth wall making. Tectonic Machines enable users to manufacture architectural elements that are specifically proportioned, incorporate a specific material knowledge, provide for a degree of variety in architectural form, and extend the skill and physicality of the (Shaffer 2009).

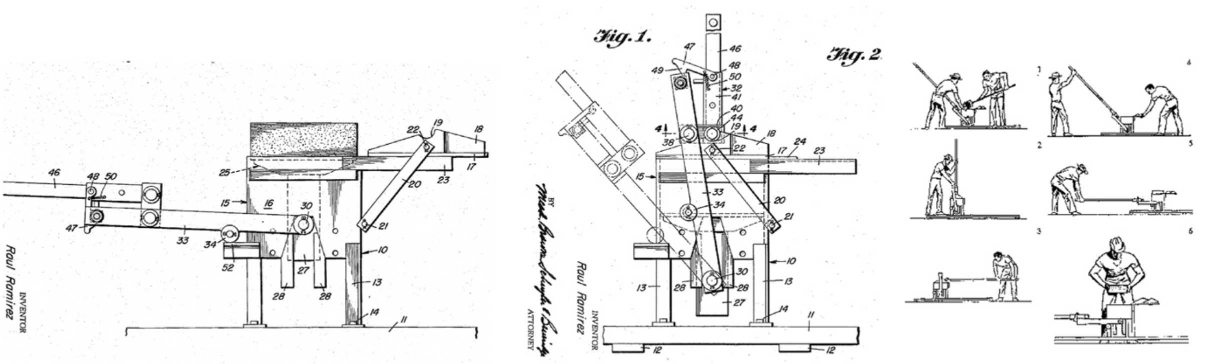

Figure 7: The CINVA Ram is a simple machine that significantly changed the labor investment in making high-quality earthen block. While the images above do not convey simplicity, the machine does not require high skill to make, operate, or repair. By easing the labor required to make earthen block and anticipating the level of skill to make/use/repair the machine, Raul Ramírez addresses *accessibility* at multiple levels. Source: (US Patent & Trademark Office 1960, IBEC Housing Corp. NY 1959)

In comparing Roto-tamper 02 to Roto-tamper 01 (Figure 8), several design changes connect to simplifying the machine for increased accessibility. Other design changes address safety and/or machine operation. In addition to the specific changes listed below, RT-01 measures 126 cm in diameter and weighs 94.6 kg, while RT-02 is smaller, measuring 100 cm in diameter and weighing 100.3 kg. RT-02 was easy to “step” back and forth in the formwork, was less prone to tipping as it completed the last layers of rammed earth at the top of the formwork, and was generally less dangerous to operate, as the potential for the machine user’s arm to be trapped between a spoke and the top of the form was eliminated with the open center of the band/wheel component in the RT-02 design. A significant redistribution of the total weight of the machine meant that no part of RT-02 weighed more than 12.5 kg (the spoke wheel of RT-01 weighed 29 kg, which violates a threshold for occupational lifting limits (25 kg). At this point in the research, Roto-tamper 02 has only been used to tamp a small preliminary wall sample measuring 92 cm x 27 cm x 27 cm. Testing the machine in constructing a full-scale wall (304.8 cm x 26 cm x 198 cm) will begin in SP 2024. Producing the smaller wall sample allowed the researcher to test the effectiveness of the machine, measure the machine user’s heart rate (HR) as an indication of labor invested in tamping, and produce an earthen sample for testing under compressive force.

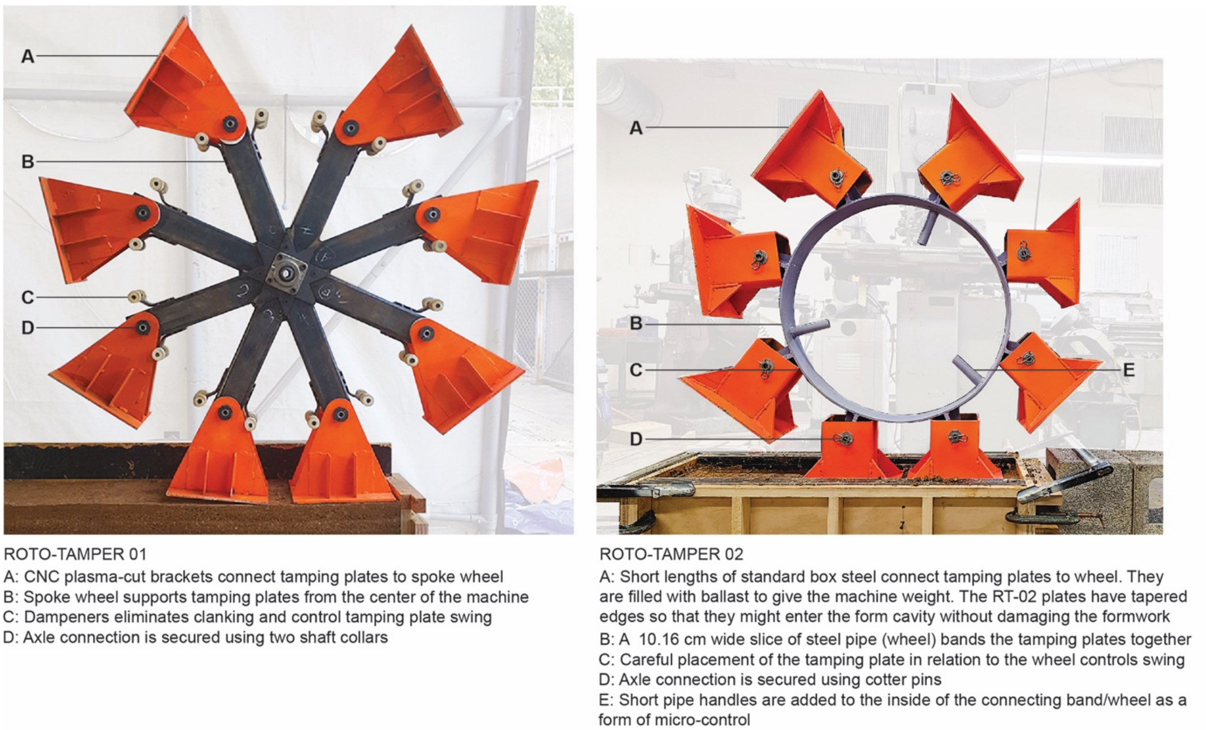

Figure 8: RT-01 compared to RT-02. Design of the second machine is directly informed by fabrication of RT-01 and the subsequent testing of RT-01 in construction of a full-scale rammed earth wall. Source: (Author 2023)

2.0 FINDINGS

Two areas for measuring the effectiveness of Rotational Tamping were addressed through the construction of rammed earth samples; energy expended in the labor of Rotational Tamping, and strength testing of rammed earth samples produced using the machines. For the sake of comparison, the researcher also recorded the expended labor required in using a hand tamper to ram earth, and in using a pneumatic tamper. Similarly, rammed earth samples made using a hand tamper and a pneumatic tamper were strength tested for comparison against earthen samples produced with Rotational Tampers.

2.1. Measuring expended energy invested in rotational

In recording heart rate (HR) information, the constructor wore Fitbit™ technology, and wile tamping, his heart rate was recorded every minute until the rammed earth sample was completed (tests began at a "resting" heart rate). The heart rate information associated with each ramming technology was recorded as mean/average, with peaks or spikes also recorded. In the table below (Table 1), heart rate recordings from four different tamping technologies (hand tamping, pneumatic tamping, and the two Rotational Tampers featured in this paper) are compared against a metric of cardiovascular response to construction *work* (Abeelhamid and Everett 2002). Findings from this assessment show that Rotational Tamping can be classified as *moderate work* compared to the *heavy/very heavy work* of hand tamping, and in comparison, to the *heavy work* of pneumatic tamping.

TABLE 1: Cardiovascular Response to Prolonged Physical Work Compared to Various Means of Rammed Earth Tamping. Source: (Adapted from Abelhamid and Everett 2002)

WORK SEVERITY	MEAN HR	PEAK HR	HAND TAMPING MEAN / PEAK HR		PNEUMATIC TAMPING MEAN / PEAK HR		RT-01 TAMPING MEAN / PEAK HR		RT-02 TAMPING MEAN / PEAK HR	
VERY LIGHT WORK	N/A	UP TO 75								
LIGHT WORK	UP TO 90	75-100								
MODERATE WORK	90 - 110	100 -125					97	108	95	111
HEAVY WORK	110 - 130	125 - 150	129		111	114				
VERY HEAVY WORK	130 - 150	150 - 175		136						
EXTREMELY HEAVY WORK	150 - 170	OVER 175								

NOTE: SOURCE: ADAPTED FROM ABELHAMID AND EVERETT (2002).

2.2. Measuring effectiveness of rotational tamping in ramming

In assessing the effectiveness of Rotational Tamping to construct rammed earth the researcher produced eight rammed earth samples using four different tamping tools/machines: a hand tamper, a pneumatic tamper, RT-01, and RT-02. The resultant samples were all the same dimensions (26 cm x 26 cm x 24 cm), were made using an identical earthen mix (local clay and shale-heavy earth, gravel, coarse sand, water), and were dried for thirty (30) days in the same environment. To compare the level of compaction across all the samples, each one was subjected to compressive force using the same 10-ton metered hydraulic press (Figure 9). The performance of each sample under mechanical compression was recorded (Table 2). Findings from this assessment show that the Rotational

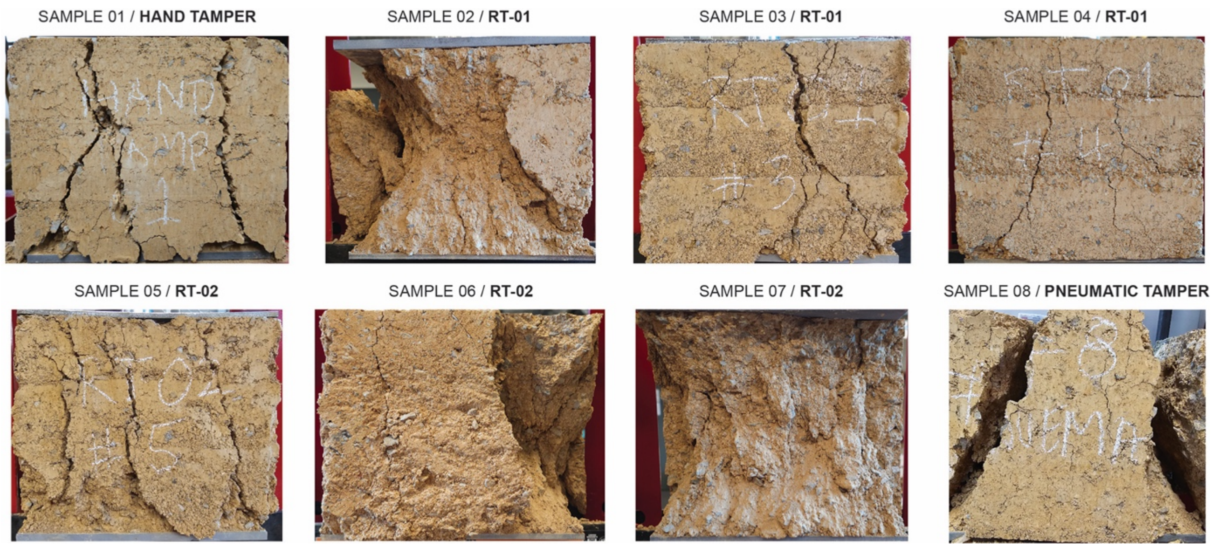

FIGURE 9: Samples used to compare the effectiveness of RT-01 and RT-02 in ramming earth. Source: (Author 2024)

Tampers compact earth to a degree that is as good as, if not slightly better than tamping by hand. Samples made by Rotational Tamper 02 are comparable to the sample made with a pneumatic tamper. These tests – using larger samples – will be repeated using more sophisticated compression testing equipment.

TABLE 2: Comparison of Rammed Earth Sample Compaction Source: (Author 2024)

	SAMPLE 01 / HAND TAMPER	SAMPLE 08 / PNEUMATIC TAMPER	SAMPLE 02 / RT- 01	SAMPLE 03 / RT- 01	SAMPLE 04 / RT- 01	SAMPLE 05 / RT- 02	SAMPLE 06/ RT- 02	SAMPLE 07/ RT- 02
FRACTURED	4.1 mt	6.9 mt	5.0 mt	5.1 mt	5.3 mt	6.2 mt	6.1 mt	6.5 mt
FAILURE	6.1 mt	7.6 mt	6.2 mt	6.3 mt	6.2 mt	7.1 mt	7.9 mt	7.7 mt

CONCLUSION

Rammed earth is an accessible form of construction that is employed globally; commonly using earthen material excavated from a building's site to construct walls that are strong, durable, and healthy for inhabitants. While rammed earth has a long history, its technological development is characterized by a significant gap between simple, accessible hand ramming tools and less-accessible mechanized tooling that includes vibrating/compacting machines, industrial robots, and factory-scale earth "printers". Another characteristic of rammed earth construction

is its labor intensiveness, with significant labor (heavy and or very heavy) required to ram earth when using hand tools and hand-held mechanized tooling. The development of Rotational Tampers for constructing rammed earth walls – simple machines closer to hand-tamping tech/tooling than pneumatic tamping machines – represent an attempt to make rammed earth construction more accessible by displacing the requisite labor into simple machines. Preliminary research presented in this paper, including heart rate monitoring during construction and compaction testing of rammed earth samples, indicate that Rotational Tamping reduces the *heavy* and/or *very heavy* work of tamping by hand or with pneumatic tooling to *moderate* work. Additionally, rammed earth samples created by Rotational Tampers compare in strength to samples created by hand tamping and pneumatic tamping. Compared to hand tamping, the Rotational tampers appear to produce rammed earth that is stronger. Compared to pneumatic tamping, the Rotational Tamper 02 appears to produce rammed earth that is similar in compaction.

The development of Rotational Tampers includes both machine design and rammed earth construction. The research will benefit from repeated rammed earth wall building tests that include a wider range of machine operators – female and male builders whose age and strength varies from teenagers to builders in their 60s. These tests will focus on the simplicity of the machine (to fabricate, assemble, disassemble, move, repair), operating the machine (easy, intuitive and safe to use), and the effectiveness of the machine (producing quality rammed earth walls using less labor). Both of the Roto-tampers in this paper were essentially built with scrap metal. Rotational Tamper 03 will factor in material cost and fabrication hours, and a recording of skills/skill level used in the fabrication process – additional factors to be considered in making rammed earth more accessible.

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REFERENCES

Abdelhamid, T.S., and Everett, J.G. 2002. "Physiological Demands during Construction Work." *Journal of Construction Engineering* 128(5): 427-37.

Amaco. 2017. "Prefabricated Rammed Earth," *YouTube Video*, 2:23. Posted January 13, 2017. https://www.youtube.com/watch?v=z5M7KG5EnB0

Bury, Jane, and Bury, Mark. 2016. *Prototyping for Architects: Real Building for the Next Generation of Digital Designers*, 12. Thames & Hudson.

Health and Safety Executive. n.d. "Construction Physical Ill Health Risks: Vibration." Accessed March 2, 2025. https://www.hse.gov.uk/construction/healthrisks/physical-ill-health-risks/vibration.htm#:~:text=Excessive%20exposure%20can%20affect%20the,Arm%20Vibration%20Syndrome%20(HAVS).

Heisel, Felix, and Hebel, Dirk. 2019. "Pioneering Construction Materials through Prototypological Research." *Biomimetics 2019* 4 (3): 56.

Lavkarbon Bygg. 2022. "Robotic Rammed Earth Construction," *YouTube Video*, 30:30. Posted December 14, 2022. https://www.youtube.com/watch?v=X0v94Ejif_Q

Safe At Work California. 2021. "Occupational Vibration Exposure." Last modified February 9, 2021. https://www.safeatworkca.com/safety-articles/occupational-vibration-exposure/.

Pacheco-Torgal, F. Jalali, S. 2012. "Earth Constructions: Lessons from the Past for Future Eco-efficient Construction." *Construction and Building Materials* 29: 512-519.

Rauch, Martin. 2023. "Rammed Earth in Building Culture." Lecture, Stuckeman School, The Pennsylvania State University, University Park, PA, October 4, 2023.