ISSN: 0972-3641

Stochastic Modeling & Applications

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Stochastic Modeling & Applications ISSN: 0972-3641

Vol. 26 No. 3 (January - June, Special Issue 2022 Part - 2) UGC CARE APPROVED JOURNAL

Stochastic Modeling & Applications

Indexing : *The journal is index in UGC, Researchgate, Worldcat*

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Gurgaon-122017 (Haryana)
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https://www.mukpublications.com

Stochastic Modeling & Applications

Special Issue

On

Recent Research on Management, Applied Sciences and Technology

Stochastic Modeling & Applications *ISSN: 0972-3641*

Vol. 26 No. 3 (January - June, Special Issue 2022 Part - 2) *UGC CARE APPROVED JOURNAL*

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Research Papers

Received: 5th January 2022 *Revised: 19th January 2022* *Accepted: 10th February 2022*

DEVELOPING ENERGY EFFICIENT OPAQUE WALL ASSEMBLY UNIT FOR WARM-HUMID AND HOT-DRY CLIMATE

ROSHNI UDYAVAR YEHUDA, VIKRAM SARAPH, RAJEEV TAISHETE, TWISHI SHAH, TRUPTI KAMAT, LALIT DAVATE

ABSTRACT

The thermal characteristics of the building envelope comprising mainly of opaque walls, roof and fenestrations have an incremental effect on the building's heating and cooling load and subsequently, the energy consumption. The Energy Conservation Building Code (ECBC) 2017 has prescribed maximum thermal transmittance values for opaque wall assembly (OWA) to achieve minimum standards of energy efficiency.

In this context, research was conducted on developing an energy-efficient OWA for hot-dry and warm-humid climate zone, in collaboration with industry partners considering sustainability, techno-economic feasibility and high thermal performance. A theoretical framework was created and benchmarks were set to evaluate 25 different design mixes which were developed in the laboratory using 150mm cubes. The block mixes were tested for compressive strength, density, water absorption, drying shrinkage and thermal conductivity as per the IS codes. Based on the benchmarking, 9 design mix prototypes were shortlisted for full-scale production in the block plant. Of these 2 were shortlisted for testing in full-scale models in Dombivli (warm-humid climatic zone) and Shrirampur (hot-dry climatic zone). Structural engineers, material scientists, architects and industry experts were involved throughout the review and consultation process over a 3-year period. The final results showed that it is possible to develop sustainable opaque wall assembly blocks with superior thermal performance than base case by 11% in hot-dry climatic zone and 0.03% in warm-humid climatic zone.

Keywords: *Opaque Wall Assembly, Energy Efficiency, Thermal transmittance, Warm- humid climate, Hot-dry climate*

1. INTRODUCTION

For centuries, buildings in India have been using burnt clay bricks as a material for external and internal walling of buildings. These blocks are not sustainable and have manifold impacts on the environment. The primary material i.e., clay is taken from agricultural fields rendering them fallow, the process using river sand which is finite and its extraction process affects aquatic life. The process of burning the bricks in kilns causes severe air pollution and the release of greenhouse gases – carbon di oxide and hazardous carbon monoxide gas especially in peri-urban areas where they are produced.

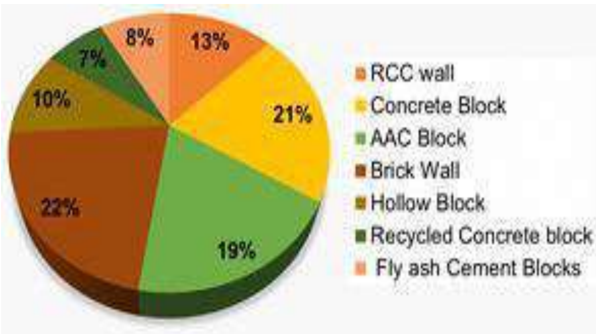

Figure 1: Walling materials currently used as per the survey conducted amongst the stakeholders of building industry.

Lastly, bricks are used along with cement plaster in buildings, which is found to have a thermal transmittance of 1.7 to 1.8 W/m^2K. This is much higher than the ECBC norms(BEE, 2018) of 0.4 W/m^2K. Hence, buildings using these materials tend to have higher cooling leads due to heat gain from the envelope. And this increased consumption occurs throughout the operational life of the building.

Only in recent years, have alternatives been developed to brick walls. These include lightweight and energy efficient AAC blocks with thermal transmission values between 0.7 to 0.8 W/m^2K and concrete blocks with thermal transmission values above 2 W/m^2K. Hence, a dire need for alternative walling material was felt.

The project aimed at developing opaque wall assembly with following characteristics:

- Low embodied energy and sustainable
- Modular - which provides flexibility and ease of assembly
- ECBC compliant
- Economical (based on life-cycle costing)

2. Review of Literature for Study of Raw Materials

Materials for OWAs were shortlisted based on thermal properties and low embodied energy. Shortlisted materials included under cementitious category: Grit, Cement, Lime, Mica, Bentonite, under organic filler materials: Bagasse, Rice Husk, Rice Straw, Bamboo Sticks, under the industry by-products: GGBS, Fly Ash, Vermiculite. Table 1 provides a summary of the industrial and agricultural as well as phase change raw materials that were reviewed along with structural and thermal properties. Usage of non-conventional materials like vermiculite, bentonite, dolomite, mica, etc. were also studied.

No.	Type of Waste & Percentage used	Type of Block	Dimension in MM	Firing/ curing	Compressive Strength (MPA)	Water Absorption %	Dry Density	Thermal Performance	Various test conducted
1	Fly Ash & GGBS (20%)	Solid	230 X 150 X 85	28 Days in open air temperature	24	8.25	1810		Density, compressive and flexural strength, water absorption (K, Venugopal, 2016)
		Hollow (35%)	304 X 150 X 110		17	9.1	1750		
2	Rice husk (30%)	Solid block	150 X 150 X 150	6 days Cured in water tank at 20± 2 °C	17.6	5.48	1797	0.71 W/mK	Density, compressive and Freezing thawing resistance, water absorption, thermal conductivity (Sisman et al., 2011)
3	Wood Ash (15%) and Foundary sand	Solid block	150 X 150 X 150	-----	28.14	<10%	2300	--	Compressive, split tensile, flexural strength, water absorption, carbonation, drying shrinkage. (Batt & Garg, 2017)
4	Cenosphere	Light weight block	100 X 100 X 100	cured in a fog room with temperatures ranging from 28 to 30 °C	small decrease or even an increase in compressive strength		at least 25% in the dry density		Compressive, split tensile strength, Dry density (Rheinheimer et al., 2017)
5	Silica Fume (25%)	Solid block	150 X 150 X 150	Cured in water tank at 20± 2C	41.4		1351.2	0.4777	Density, compressive strength, porosity and thermal conductivity (Farhan et al., 2012)
	Microwave	Solid block	150 X 150 X	Cured in	35.6		1344.56	0.4273	

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	Incinerated Rice Husk Ash (25%)		150	water tank at 20± 2 C					
6	Rice Husk Ash (20%)	Solid block	150 X 150 X 150		6.88		500-2100		Density, compressive strength, costing (Sangeetha, 2016)
7	Rice Husk Ash (20%)	Solid block	150 X 150 X 150		16.03	1.86			Compressive, split tensile, flexural strength, water absorption (Krishna et al., 2016)
8	Saw Dust Ash (5%)	Solid block	150 X 150 X 150		32.44	1.245	2475		Density, compressive strength, water absorption (Malik et al., 2015)
9	Dolomite (10%)	Solid block	150 X 150 X 150		31.24				Compressive, split tensile, flexural strength (Preethi & Arulraj, 2015)
10	Expanded Perlite Aggregate (10%)	Light weight block	100 X 100 X 100	wet stack 28 days curing	37.5	4.07			Compressive, split tensile strength Apparent Porosity, Normal and cracked Sorptivity (Khonsari et al., 2010)

Table 1: Review of researches done in the field

3. FORMULATION OF MIX DESIGN:

A Sustainability Parametric Evaluation tool (SPET) for sustainable building materials based on 47 criteria under 5 major heads namely, safety, ease of use, physico-chemical properties, sustainability and market factor, was devised. This was used, for scoring the sustainability ranking of building materials as well as individual raw materials. Materials for OWAs were shortlisted based on thermal properties and SPET score. Shortlisted materials included under cementitious category: Grit, Cement, Lime, Mica, Bentonite, under organic filler materials: Bagasse, Rice Husk, Rice Straw, Bamboo sticks, under the industry by-products: GGBS, Fly Ash, Vermiculite. Materials were shortlisted based on availability in India. Limestone, Rice Straw and Rice Husk were found to be available in plenty. Usage of Bamboo, also had potential social benefits through employment and livelihood in rural areas.

The shortlisted innovative materials were categorized as base, binder and filler based on physio chemical properties, and 24 unique mix designs were formulated using the dry mixing process by percentage of weight with Godrej (Industry Partner) M10 concrete blocks as base.

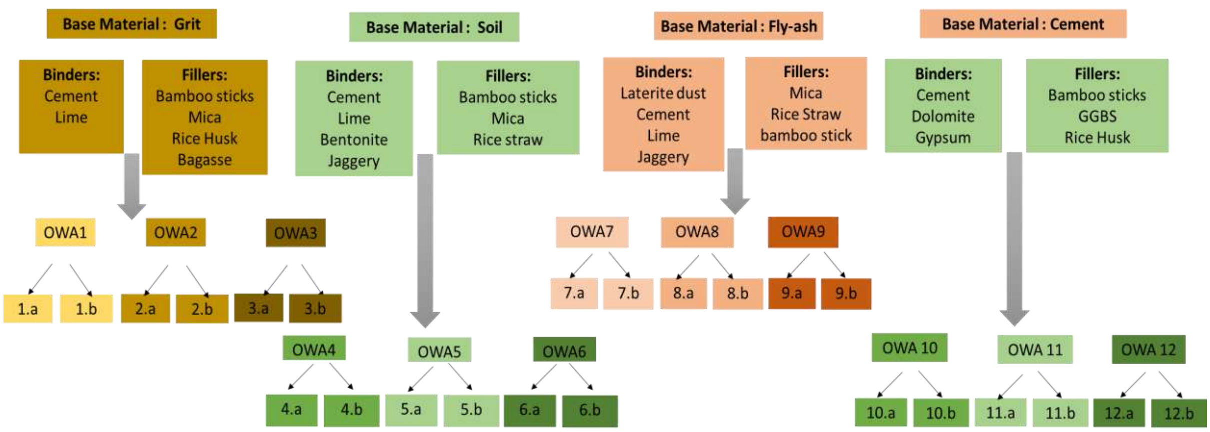

Figure 2: Initial Developed designs for material assemblies

4. Performance Benchmarks for the New Owas:
The formulated mix deigns were cast into 150mm cube in lab and tested for compressive strength, water absorption and density after 7 days, 14 days and 28 days respectively of curing. The blocks were then cast into 1m x 1m wall assemblies to be further tested for their thermal performance in a specially designed 'Hot guarded box' testing facility.

As these blocks were different from conventional OWA, target parameters for new design mix were finalized in consultation with experts and the industry partner. The benchmarking was derived from various IS standards related to blocks, masonry and materials as follows:

1. Compressive strength – 3.5 - 5 N/mm2
2. Density – 1500 kg/cu.m (brick)
3. Water absorption <10%
4. Drying shrinkage – 0.05
5. Thermal Transmittance – 0.4 W/m2K (ECBC)

5. Shortlisting and Improvisation of Mix Designs:
5.1 Screening 1: Amongst the 24 mix designs, the mixes having jaggery were eliminated, as they faced major issues during casting of blocks. The testing of blocks for compressive strength, density and water absorption was done as per IS standards in the QC lab of industry partner. Nine mix designs were shortlisted based on the set performance benchmarks.

5.2 Screening 2: The 9 mix designs were revised to improvise the performance of these blocks with respect to structural and thermal performance and cast into blocks of size 390 mm x 190 mm x 140 m (production size of concrete blocks).

At this stage, in addition to the compressive strength, density and water absorption, thermal performance and drying shrinkage were also measured.

For measurement of the Thermal Transmittance, a hot guarded box was designed in which 1m x 1m wall of the shortlisted prototype was subjected to a temperature difference on either side of more than 15^0C within the hot guarded box after which testing using a U- value meter is conducted for every 15-minute interval. The temperature differential was maintained using a sensor and cut-off device. The surface temperature and radiant temperature were also measured so as to understand radiant heat properties of the material.

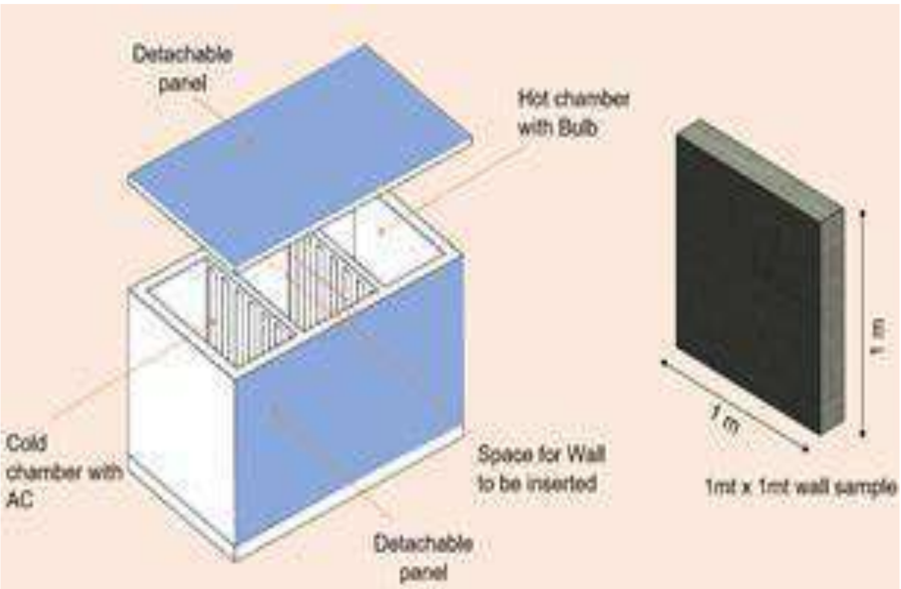

Figure 3: Thermal performance Testing Facility – Hot guarded box

The Drying shrinkage tests were done through a certified third-party lab. As shown in the table below, the two best performing Mix designs were selected for full scale prototype testing – one each in hot-dry and warm-humid climate. The criteria for selection for the different climate zones was based on material availability and thermal transmittance (lower U-value for hot dry climate was considered).

Name of block	Constituents	Compressive Strength (N/mm2)	Density (Kg/m3)	Water Absorption (%)	Weight of block (Kg)	Thermal Performance U Value (W/m2)	Drying and Shrinkage (%)
AE2M1	Cement, Lime, Metal 0, Metal 1, Mica Powder, Bamboo mat	5.72	2053	5.13	19.9	2.5	-
AE2M3	Cement, Lime, Metal 0, Metal 1, Mica Powder, Shredded Bamboo	5.75	2203	6.44	21.62	-	0.03
AE3M1	Cement, Lime, Metal 0, Metal 1, Mica Powder, Rice Husk	5.7	1928	5.24	18.72	1.4	0.03
BE2M1	Cement, Bentonite, Metal 1, Mica Powder, Rice Husk, Dolomite	1.52	1590	7.02	15.1	3.07	0.04
CE2M1	Cement, Laterite dust, Metal 1, Mica Powder, Vermiculite, GGBS	2.67	1666	5.6	16	1.03	-
CE2M4	Cement, Laterite dust, Metal 1, Mica Powder, Vermiculite, GGBS	2.16	1295	5.16	12.5	4.55	0.04
CE3M3	Cement, Laterite dust, Metal 1, Mica Powder, Vermiculite, Dolomite	1.96	1739	5.36	17	0.7	0.04
DE3M1	Lime, Fly-ash, Metal 1, Mica Powder, Rice straw powder, GGBS	2	1870	8.5	19.26	8.11	-

Table 2: Results of shortlisted Mix Design

Improvisation of finalized mix designs

- AE3 M1 - The compressive strength and other parameters were found satisfactory, while thermal performance needed to be improved. Accordingly, the quantity of Metal 1 and metal 0 were reduced, replaced by increasing the percentage of Mica.
- CE3 M3 - The thermal performance and other parameters were found satisfactory but compressive strength needed to be improved. Accordingly, the quantity of Mica and Vermiculite were reduced, replaced by increasing the percentage of Cement, Laterite dust and Metal 1.

6. Thermal Testing of full-Scale Prototypes

Full-scale models (100 sq. ft. area and 1000 cu. ft. volume) designed based on literature review, were erected 2 each in Shrirampur (hot dry climate) and Dombivli (warm humid climate), one each in each climate zone being base case.

Base case in warm-humid was made of AAC blocks and base case in hot-dry climate was made of clay-fired bricks. For the Design or Proposed case, CE3M3 was shortlisted for warm-humid climate while AE3M1 was shortlisted for hot-dry climate.

For analysis of the thermal performance of the OWAs in the full-scale prototypes, following thermal properties were measured:

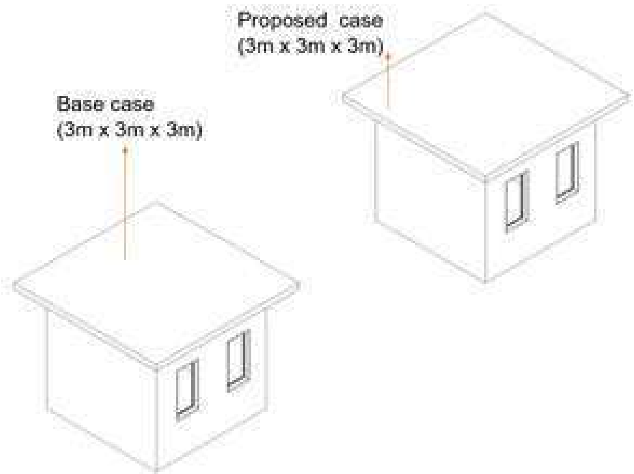

Figure 4: Full scale Prototype

1. Surface temperatures: 48-hour surface temperature recorded using data logger and thermocouple sensors to obtain ΔT and calculate U-value.
2. Mean Radiant Temperature (MRT): 12-hour hourly MRT was calculated using formula (Goldman 1978), for which globe temperature and dry bulb temperature were measured using a digital globe thermometer and air velocity using a calibrated anemometer.
3. Thermal transmittance: U value was also measured using U-value meter and the hot Guarded box as well as from thermal conductivity tests using certified third-party laboratory.

7. Findings and Discussion

a) Warm Humid climate: U-value of design blocks was in the range of 0.77 to 1.21. Its thermal performance was close to AAC blocks but having much lower embodied energy.

The internal and external wall surface temperatures of both prototypes i.e., design and base has nearly similar reading.

The walling materials of design case, thermally works equivalent to the AAC blocks, i.e. the base case walling but it has a low embodied energy having no autoclaving and other intensive processes required in preparing AAC blocks.

The average mean radiant temperature of base case was cooler than the design case by half a degree Celsius.

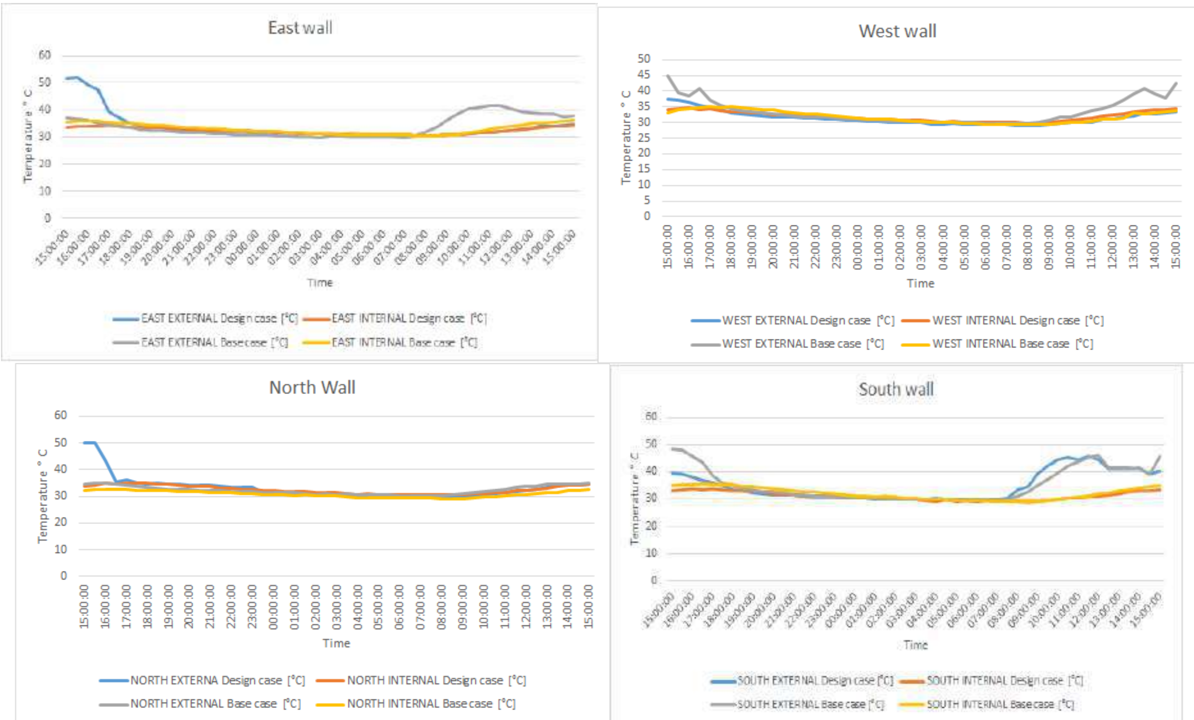

Figure 6: Surface Temperatures - Dombivli

Plate 1: Performing thermal measurement

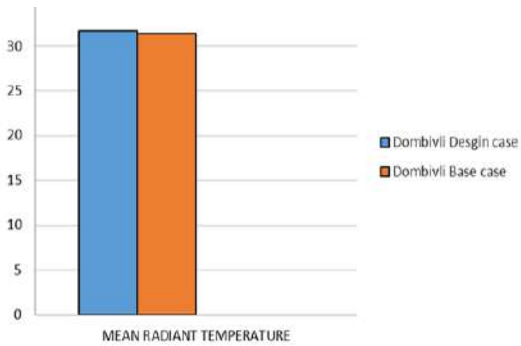

Figure 7: MRT calculated

b) Hot and Dry Climate:
U-value of design blocks was in the range of 1.18 to 1.28. Its thermal performance was much better than bricks in the base case. The external surface temperatures of wall in design case was found to be around 5^0C lower as compared to that of base case. This shows that the design case wall assembly reflects more heat as compared to base case walling i.e., bricks. This could be predominantly due to color and textures of blocks.

The difference between the external and internal wall surface temperature of design was around 2^0C whereas in base case it is around 5^0C.

Figure 8: Surface Temperatures – Shrirampur

Plate 2: Recording hourly measurements

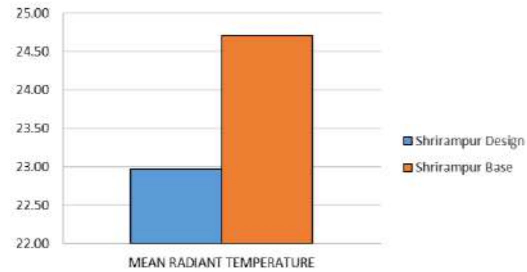

Figure 9: Mean Radiant temperature.

The average of mean radiant temperature of design case was lower by 2.5^0C than that of base case. This observation is in synchronization to radiant wall temperature reading of both the cases.

8. CONCLUSIONS

Both OWAs performed better than brick and concrete, the two most conventional OWAs used today. The project has shown that it is possible to develop energy efficient, low embodied energy OWAs to meet the demands of the market. The products developed are both energy efficient, cost effective and sustainable than those currently available in the market. There can be much more improvement in the product with improved design mixes, use of other alternative and waste materials to develop a product that is light weight, low cost, modular, easy to transport and energy efficient.

ACKNOWLEDGEMENTS

The project is funded by the Department of Science and Technology (DST), Govt. of India through its scheme entitled 'Initiative to Promote Habitat Energy Efficiency' (IPHEE). It is being conducted under the aegis of Science & Technology Park, Pune. Industry partner, Godrej Construction has provided the testing facilities and infrastructure and additional technical support has been provided by industry partner, Panasia Engineering Ltd., Mumbai.

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