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Deserts turned to glass: The research behind the Mirage Sculpture

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ABSTRACT: Located in Apple Park in California (USA), Mirage is an outdoor sculpture of 448 solid cast glass cylindrical columns, each 210cm high and 15cm in diameter, made from 70 different desert sands. The sculpture by Katie Paterson and Zeller & Moyer involved a large team of artists, architects, geologists and scientists. This paper discusses the experimental work conducted by TU Delft on developing glass compositions of the desired colour, hue and tint, as a function of foreign, impure sand addition to the basic batch recipe. XRF and XRD analyses of the desert sand samples revealed their chemical composition and crystallographic structure, purity level and presence of undesired contaminants. Repetitive melting experiments led to establishing relationships between the sand characteristics and the colour hue, tint and intensity of the resulting glass, concluding to 0.02–17% desert sand content as substitute of the original, low-iron sand in the batch recipe. Iron oxides were identified as the prevailing colour agents, yielding a colour palette of blue, aquamarine and green hues based on their oxidation state. The melting experiments led to the formulation of a glass recipe prediction model and to modifications of the standard batch, towards achieving the desired colour gradient while preventing critical defects in the glass. The vertical casting of the columns by the glass studio gave a distinct surface pattern with recess lines and a high bubble content. To identify if the strength is governed by the surface quality, the bubble content or the glass's chemical composition and to attain representative strength data, 4-point bending tests were conducted on 37.5x51x635mm beam specimens produced by the same foundry. Fractography analysis of the tested specimens showed that the characteristic surface pattern governs the design strength. Mirage was inaugurated in May 2023, showcasing the potential and versatile beauty of using a wide range of impure sands in glass making.

1 INTRODUCTION

Located in an olive grove next to the Visitor Center at Apple Park in Cupertino, California, *Mirage* (<https://mirage.place/>) has been envisioned by artist *Katie Paterson* and architects *Zeller & Moyer* as a glass sculpture, where visitors can walk around it and experience all desert landscapes of the world. The inspiration behind the glass sculpture is the natural origin of glass in deserts, when sand is struck by a lightning. In specific, the public sculpture consists of 3 curved walls that meander between the olive trees, comprising a total of 448 cast glass columns, each circa 2 m high and 0.15 m in diameter, made of sand from 70 deserts from around the world (Figure 1). The collected sands spanned from subtropical and coastal deserts to mountainous, volcanic and even fossilized deserts. Each of these sands has a different and unique, chemical composition, resulting in 70 different glass recipes with different types of contaminants.

The desire of the design team was to use the 70 sands “as-collected”, thus with impurities, and achieve the desired hues and subtle colour transition without any additive colourants. The project

involved a large team of artists, architects, geologists and desert experts. TU Delft team's primary role was to inform the design, engineering and manufacturing process of the cast glass columns, by (i) experimentally studying, defining and predicting glass compositions that would yield the desired colour gradient and hues without any added colourants and (ii) assessing the influence of foreign, impure sand additions to the strength of the cast glass.



Figure 1. Mirage, in Apple Park, California.

2 METHODOLOGY

The relevant R&D was divided into 4 phases:

- (i) Initially, X-ray Fluorescence (XRF) and X-ray Diffraction (XRD) analyses were performed in desert sand samples, to reveal their chemical composition, crystallographic structure, iron oxidization state, purity level and presence of undesired contaminants.
- (ii) Following, melting experiments on a selected number of desert sands were carried out to establish relationships between the sand characteristics and the colour hue, tint and intensity of the resulting glass, in order to formulate a glass recipe prediction model.
- (iii) In parallel, 4-point bending tests and post-failure fractography analysis were conducted on 37.5x51x635mm beam specimens produced by the glass foundry to identify the strength of the cast glass columns and determine the governing factor of failure (surface quality, variable compositions and contaminants, bubble content).
- (iv) Based on all the above, the TU Delft team advised on the final production of the cast glass columns, and in specific, on the casting sequence and on modifications of the standard batch towards achieving the desired colour gradient while preventing critical defects in the glass and tackling the logistical challenges of the final casting process.

3 EXPERIMENTAL

3.1 Sand compositional analysis

Sands may consist of various ingredients in various ratios, which in turn can result in variable glass colours and contaminants. Thus, obtaining the chemical composition of each sand was essential.

All sands were initially shipped to East Bay Batch and Color in California; a process that spanned multiple months. A small sample of each collected and sieved desert sand was then shipped to TU Delft in the Netherlands, where XRF analysis was conducted to derive its chemical composition. The results were recorded in an extensive excel datasheet, where the presence of elements that could lead to defects, such as high Calcium oxide (CaCO_3) or alumina content (Al_2O_3), was identified and recorded. The XRF analyses of the sands can be found in: <https://mirage.place/sands/>

The artistic vision was that *Mirage's* colouration is a direct expression of the desert sands without any added colourants. Iron (Fe) oxides were identified as the main colourant in all the deserts. Depending on its oxidation state, ferrous (FeO) or ferric (Fe_2O_3), iron in the glass can yield

either blue or green hues (Schreurs and Brill 1984, Simpson and Myers 1978, Zschimmer 1913). The oxidization state of the iron was identified via XRD analysis on sand samples. An interesting finding was that there is a direct correlation of (black) sands with ferrous iron with locations of volcanic origin (i.e. Iceland, KaŪ - Hawaii, Antarctica) as shown in Table 1. Red sands would suggest a high percentage of ferric oxide yielding green colours, while light in colour sands would typically have a high silica content and thus could yield clear glass (see Figure 2).



Figure 2. Main sand colours and predicted glass colour hues.

Table 1. Results of XRF/XRD analysis of characteristic sands.

Desert name	Si%	Fe Oxidiz. State, %	Other colourants			Main other element (%)	Predicted colour
			CuO %	Cr ₂ O ₃ %	MnO %		
Iceland	39.92	FeO	-	0.07	0.26	Al ₂ O ₃	B
		16.03				23.02	
Antarctica	56.31	FeO	0.01	0.06	0.12	Al ₂ O ₃	B
		7.48				15.01	
Ka'Ū	40.97	FeO	0.02	0.12	0.16	MgO	B
		13.82				9.96	
Arctic	64.03	FeO/Fe ₂ O ₃	0.01	0.02	0.07	Al ₂ O ₃	A
		6.71				21.56	
Ataca-ma	65.10	FeO/Fe ₂ O ₃	0.01	0.01	0.05	Al ₂ O ₃	A
		4.10				17.50	
Ordos	3.61	unk	-	-	0.05	CaO	C
		0.90				91.14	
White	97.98	unk	-	0.05	0.01	Al ₂ O ₃	C
		0.76				0.56	
Chihuahua	68.15	Fe ₂ O ₃	-	-	0.05	Al ₂ O ₃	G
		3.20				16.27	
Lomp-oul	87.70	Fe ₂ O ₃	-	-	-	Al ₂ O ₃	G
		0.62				7.05	
Cyclades	60.83	Fe ₂ O ₃	-	-	0.04	CaO	G
		1.40				21.11	
Sahara	93.49	Fe ₂ O ₃	-	0.04	-	Al ₂ O ₃	G
		1.12				1.86	
Mojave	98.73	Fe ₂ O ₃	-	0.02	-	Al ₂ O ₃	G
		0.35				0.58	
Great sandy	82.55	Fe ₂ O ₃	-	0.02	0.01	Al ₂ O ₃	G
		4.42				11.59	
Great Rann	0.24	Fe ₂ O ₃	-	-	-	Na	G
		0.04				42.37	

B = blue, A = aquamarine, C = clear, G = green.

3.2 Melting experiments

Conducting melting tests in all sands was financially and logistically not possible, as multiple sands only arrived in USA after the final production of columns had started. It was therefore essential to form a reliable prediction model that could yield the exact desired hue and colouration per sand and identify any critical defects due to impurities. To create this model, repetitive melting experiments on a selection of ~20 characteristic sands were performed at TU Delft's cast glass facilities, so that the relationships between the sand characteristics and the colour hue, tint and intensity of the resulting glass can be established.

The chosen sands were selected to represent variable % of chemical elements, particularly of silica (SiO_2), Alumina oxide (Al_2O_3) and iron oxide (FeO or Fe_2O_3) content – characteristic examples are shown in Table 1. Aim of the melting tests was to determine the % of each desert sand that would substitute part of the basic batch, based on sand availability (in some cases, only a few grams of a desert sand could be collected) and the desired hue and tint, and while preventing critical defects from emerging. To ensure that the small-scale experimental results would not deviate from the large-scale final castings at the selected production foundry, it was important to simulate as accurately as possible the casting method of the *John Lewis Glass Studio* in TU Delft's lab facilities.

Accordingly, the process was as follows: a % of the low-iron sand used by the John Lewis foundry was replaced with desert sand; the remaining elements of the batch were used in the same %, as shown in Figure 3. The batch composition concerns a modified soda-lime silica glass, suitable for casting.

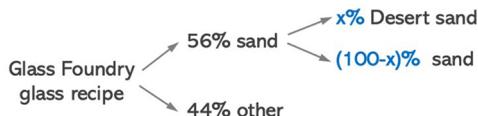


Figure 3. Approach of mixing the desert sand with the standard batch by the glass foundry.

The mix was placed into pure alumina crucibles in order to found glass at 1350 °C in a Carbolite HTF 17/10 furnace. The glass was then repoured into 15 cm long beams at 1020°C and annealed at 512°C using a ROHDE ELS 200S kiln. The beams would be then ground and polished manually up to a 600 grit, in order to be visually evaluated in terms of colour density and defects. The 15 cm length of the beams was chosen to reflect the final diameter of the columns, enabling a direct assessment of the final colour density. In the initial

explorative stages, a selection of 8 desert sand samples were cast in several set percentages such as 3%, 5%, 8%, 10%, 13%, 15% and 20%.

The colour results were at a large extend predictable: The Fe% content and its oxidization state (FeO or Fe_2O_3) governed the final colour in all cases, yielding hues of green, aquamarine and blue, as schematically shown in Table 2. In principle, the higher the Fe content in the initial mix, the darker the resulting hue would be. However, deviations in other elements in the composition further affected the intensity of the colour. Overall, the higher the % of impure sand used, the more pronounced the tone would be in the same Fe%, as shown in Figure 4.

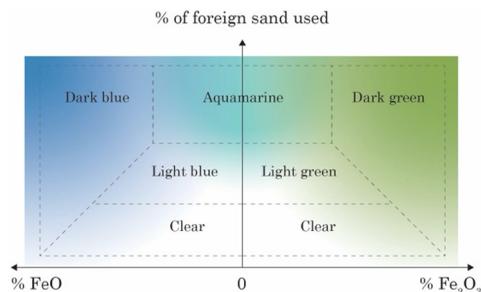


Figure 4. Schematic illustration of the colour hue based on Fe % and oxidization status and % of foreign sand used in the final batch. The depicted hues are indicative and are not representative of the real glass colours.

An example is shown in Figure 5: the sample with 0.09% Fe_2O_3 calculated content from 5% *Chihuahua* desert sand replacing the basic batch, is lighter in colour compared to the sample with 0.07% Fe_2O_3 content made from 20% *Lompoul* desert sand replacing the standard batch.



Figure 5. Estimated Fe_2O_3 % in cast glass beams. The higher the foreign sand % used, the more prominent the colour intensity.

Moreover, the reduced, ferrous (FeO) iron would react with the antimony oxide (Sb_2O_3) included in the standard batch and further oxidize (to Fe_2O_3), leading to all sands yielding hues of green. To obtain blue hues, in alignment with the artistic vision, Sb_2O_3 was removed from mixes of desert sands that had been identified to have iron

in its ferrous state (FeO). An example of the influence of Sb_2O_3 presence in sands with FeO content is shown in Figure 6. In principle, the reduced colours (without antimony in the batch), would appear much darker at the same % of sand; this was taken into consideration in the prediction model.

In terms of critical defects, these mainly concerned unmolten material and crystallization, mainly in sands with high CaO content (e.g. sands with high fossil content – such as the Cyclades desert in Table 1), or high-melting elements such as Chromium (Cr). In such cases, a lower desert sand % in the batch was advised.



Figure 6. Same % of Iceland (ferrous) sand cast using a standard batch with (left) and without (right) antimony oxide.

Based on the melting experiments, a colour prediction model was established in an excel file, which was further calibrated via the production of the first final columns at the glass foundry. The results indicated a good match in colour alignment between the small-scale beam specimens cast in TU Delft and the final columns produced in John Lewis Glass Studio (Figure 7).

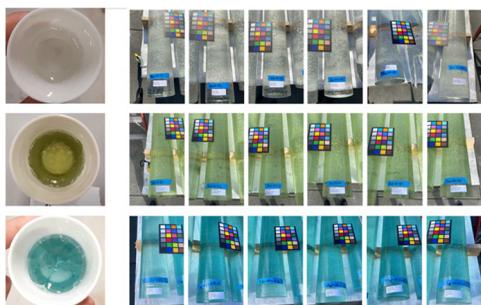


Figure 7. Alignment of cast glass samples at TU Delft (left) and final columns cast in the John Lewis Glass Studio (right).

Based on the melting tests, the sculpture would comprise cast glass columns of 4 main hues -clear, green, aquamarine, blue- in the desired, progressive, colour intensity, produced with as little as 0.02% and as high as 17% desert sand content, as shown in Table 2.

Table 2. Desert sand & final Iron oxide % range per colour.

Colour	Desert sand %	Final iron %	Iron oxid. state	Sb_2O_3 in mix
Clear	0.02-1	0.0001-0.008	Fe_2O_3	yes
Green	1-17	0.0095-0.25	Fe_2O_3	yes
Aquamarine	0.02-1.6	0.0014-0.14%	Fe_2O_3 , FeO	no
Blue	0.02-1.6	0.0014-0.14%	FeO	no

3.3 Production of cast glass columns

The final columns were produced at the *John Lewis Glass Studio* in Oakland, California. The oven where the glass was formulated has a total capacity of ~ 1360 kg. Each column weighs ~ 120 kg; thus, accounting for material loss during the founding of glass (20%), leftover residue in the glass oven and possible discards, a full batch in the furnace could yield in principle 6 - 7 columns. This fact determined the number of columns per desert sand. Moreover, it was important that the furnace could run continuously; rinsing between batches would skyrocket the manufacturing costs both in terms of time and materials. Thus, to achieve the desired colour and hue gradient, the recipes were sequenced considering potential cross-colour-contamination from the previous recipe's residue. Hence, in principle, first the purest sands offering the lightest hues would be cast, successively proceeding to desert sand mixes that would yield darker hues of the same colour. Sands in little available content or containing elements that could lead to contamination (e.g. Cyclades sand) were used in small amounts to yield either colourless columns, or as *cleansing sands* when switching between glass recipes with and without antimony oxide (Sb_2O_3) to prevent cross-contamination of the latter from the former.



Figure 8. Casting of a glass column at John Lewis Glass Studio.

The glass columns were vertically cast in a steel mould with a graphite coating (Figure 8), which was controllably pre-heated with a flame, before it was placed under the kiln with the molten glass. Upon opening a lid, the molten glass would pour

in the form of a strip until it would fill the mould. This vertical casting process resulted in two characteristic features in the cast glass, shown in Figure 9: (i) a characteristic lining, similar to the layered surface of a 3D printed glass, due to the relatively high viscosity of the molten glass as it coiled down the mould and its local solidification when it came into contact with the considerably colder mould surface; (ii) a considerable amount of bubbles in the bulk, more prominent in some recipes than others due to viscosity fluctuations. The bubble content was higher at the bottom of the cast columns. Therefore, to avoid having a high content of bubbles at the ground connection, all columns were installed upside down compared to the way they were cast.



Figure 9. The resulting bubble content and surface texture of the cast glass columns.

3.4 Mechanical testing

For the structural verification of the sculpture, it was detrimental to determine which factor governed the strength of the cast glass columns: (i) the glass recipes, (ii) the characteristic lining texture of the glass, or (iii) the bubble content. Accordingly, a series of 4-point bending experiments using an Instron 1251 (100KN) were conducted at TU Delft on 12 vertically cast glass beams made with the standard recipe of the John Lewis studio, each 37.5x51x635mm in dimensions. Prior to testing, each beam was checked using cross-polarization for internal stresses and its bottom surface lining pattern was mapped using a Polyvinyl Siloxane mold.



Figure 10. Beam specimen under 4-point bending using DIC.

To accurately measure the displacement and the flexural strength of the glass beams, each beam

was sprayed with a speckle pattern so that *Digital Image Correlation* (DIC) can be used (Figure 10). The fixtures were set at a load/support span of 250/500mm and a loading rate of 0.2mm/s was used. Upon failure, all beams were inspected under a *Keyence VHX-7000 Digital Microscope* to identify the origin of the failure crack. The results indicated that crack initiation always occurred at one of the characteristic linings (Figure 11), indicating in turn that the surface texture of the columns governed their strength rather than the bubble content and/or the various glass recipes.

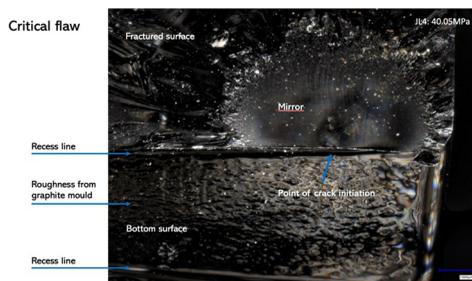


Figure 11. Fractography analysis of the critical flaw in one of the tested glass beams.

4 CONCLUSIONS

The sand analyses and melting experiments demonstrate that in all 70 desert sands the governing colourant is iron oxide. When present in ferric state (Fe_2O_3) it can yield green hues, when in ferrous state (FeO) it can yield blue hues in glass. To achieve blue hues, antimony oxide (Sb_2O_3) must be removed from the batch recipe as it can further oxidize the iron.

The intensity of the glass colour is further affected by deviations in other elements in the composition. In principle, the higher the % of impure sand used, the more pronounced the tint in the same final Fe%.

Based on the melting tests, the sculpture comprises cast glass columns of 4 main hues -clear, green, aquamarine and blue- in the desired, progressive, colour intensity, produced using 0.02% -17% desert sand.

Critical defects occurred primarily in glasses made from desert sands with high CaO content and/or Cr_2O_3 , which in turn would result in unmolten material and crystallization. Sands identified to potentially cause critical defects were used in small %.

Logistical challenges with the final casting of the columns determined the number of glass columns per desert sand (6-7) and required the sequencing of the sand batches to minimize colour cross-contamination.

The vertical casting of the columns results in a characteristic lined surface texture and to a high

content of bubbles. 4-point bending tests and fractographic analysis on vertical cast glass beams produced by the glass studio, revealed that the columns' strength is governed by the characteristic lined surface.

Overall, the project showcases not only the variety and extent of Earth's deserts but also the potential of using locally sourced sand as raw material for producing glass, and the aesthetic



Figure 12. The Mirage Sculpture.

value and unique character of defectful glass (Figure 12).

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