Deep Layers of 'Flatland':

Scaling Up Nanomaterials

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An understanding of surfaces is inherently problematised through the notion of scale. We are all aware that even the smoothest surface, when magnified, may reveal troughs, pits, cracks and lumps imperceptible to the human eye or touch. The ability of scientists and engineers to understand and 'view' the nanoscale – made possible by the creation of high-powered microscopes such as scanning electron microscopes (SEMs), atomic force microscopes (AFMs) and scanning tunnelling microscopes (STMs) – has allowed the surfaces of materials to be explored at scales never before accessible. Yet, as has been noted by de Ridder-Vignone and Lynch, the means by which these microscopes 'see' is extremely different from the means by which humans perceive their environments, meaning that readings from this equipment must be translated into forms which 'resemble recognizable objects, surfaces and landscapes'.[1] There is 'no established "true" way to depict nanoscale entities and surfaces',[2] they write, also noting that 'the instrument does not reveal what an imaginary nanoscale observer could possibly see'.[3]

The philosopher Avrum Stroll distinguished between two means of viewing physical surfaces: the "ordinary person's" and the scientists' conceptions. While an ordinary person, at the 'macroscopic level' may see 'scratches, marks, blemishes' within a surface which can be 'checked with the naked eye or by feeling the surface', a scientist's account of the surface, 'a last layer of atoms', cannot be touched or seen.[4] Stroll concludes that the ordinary person's perception of an object is incompatible with the scientific account. They describe fundamentally different objects: a macroscopic view of a baseball sees one surface, but a microscopic view may see many surfaces.[5] Yet what does this distinction mean for those who work on the scale-up of nano-technologies? Those whose concern is not only the atomic structure of a material but also the production of technologies on the factory scale?

Entering "Flatland"

The '2D' nanomaterial graphene, first isolated at the University of Manchester by professors Andre Geim and Kostya Novoselov in influential, Nobel-Prize winning

[1] de Ridder-Vignone and Lynch, 2012: 448
[2] de Ridder-Vignone and Lynch, 2012: 448
[3] de Ridder-Vignone and Lynch, 2012: 447
[4] Stroll, 1988: 61
[5] Stroll, 1998: 62

work described in a 2004 paper in the journal *Science*,[6] demonstrates well the complications of scale in the understanding of surfaces. In a now mythologised (and much simplified) story, Geim and Novoselov took as a starting point a technique used by physicists to clean the surface of graphite rock – using sticky-tape to peel the outermost layers of the rock. However, instead of discarding this sticky-tape and graphite residue, Geim and Novoselov continued to use the tape to peel it into thinner and thinner layers. Graphite is composed of layers of carbon atoms stacked on top of one another, and eventually the two scientists were able to reduce this graphite residue to just a single layer of these carbon atoms. Though it was not the discovery of graphene (the material had been studied for several decades and was first given the name *graphene* in 1986,[7] but had been thought not stable enough to exist in an isolated form), the 2004 isolation constituted the re-discovery of graphene as a 'wonder material'.[8] Geim and Novoselov documented in their 2004 paper the material's astounding electrical properties, and subsequent research explored many other interesting characteristics – it is more conductive of electricity than copper, more conductive of heat than any other material, highly flexible, almost entirely transparent, and the strongest material known.

So from within the surface of graphite emerged a 'wonder material'; from a process used to clean impurities from the outermost layers of graphite emerged the first 2D material. Graphene, like the thousands of other 2D materials which followed in its wake, is itself *essentially all surface*. These materials could be said to have as little depth as physically possible. In this single layer form, 2D materials can take on properties which are 'very different from those of their 3D counterparts'.[9] Through the emerging field of 2D materials, scientists have been able to enter what Novoselov calls 'flatland' – a reference to the novel of the same name by Victorian author Edwin Abbott.[10]

The prospects of this exploration of 'flatland' could have very real implications on our 3D world; rather than occupying some distant realm, accessible to only those scientists with the expensive machinery to explore it, both 2D materials and other nanomaterials are increasingly shaping the world around us. Understanding, depicting and, indeed, manipulating materials on the nanoscale is increasingly a matter of concern for scientists, engineers and even designers.[11]

[6] Novoselov et al., 2004
[7] Boehm et al., 1986
[8] Geim, 2010
[9] Novoselov, 2011: 840
[10] Novoselov, 2011
[11] See Daston and Galison, 2007: 397, who argue that the depiction of the nanoscale is inherently tied to manipulation and use.

Over the last few years, products and materials utilising 2D materials (for example, in energy storage devices, electronics and composite materials) have come to market, and the following decades are likely to see significantly more. There is also the possibility that, by essentially reversing the process that led to the isolation of graphene (breaking down a 3D structure to isolate its component layers), new materials, known as heterostructures, might be produced through the stacking of 2D layers of different materials to produce new hybrid materials with specific and 'tunable' properties:

> Thus a completely new world of 'materials on demand' is opening up to us. Because the pool of the original 2D crystals is very rich, the properties of such heterostructures can cover a huge parameter space, combining characteristics which previously we would not even dare to think of being found together in one material.[12]

As yet, however, there still remains a gap between the interesting phenomena observed by scientists exploring 2D materials, and the ability for these phenomena to be harnessed through technological applications. At the University of Manchester, the institution created the Graphene Engineering Innovation Centre (GEIC) explicitly to tackle this 'gap'. The GEIC, opened in 2018, is the second graphene specialist facility built at the university, after the National Graphene Institute (NGI) in 2015.[13] The centre is concerned with the scale-up of 2D material technologies through collaborations between the university and industry – with some industry partners of the GEIC renting their own private laboratory space within the building, ultimately as a means of translating its technical and scientific expertise in the emerging field of 2D materials into more profitable forms of knowledge through the creation of IP. While popular narratives describing technological discoveries often attempt to pinpoint the moment of inception, and the geniuses behind them, from which a principle or technology emerges and diffuses throughout society,[14] a key insight of Science and Technology Studies is that building a scientific fact or technology inherently requires the building of robust networks through which they are able to circulate through processes of translation.[15] The GEIC represents a facility which looks to establish these networks and engage in processes of enrolment and translation, in order to transform scientific and technological principles observed at the scientific laboratory scale to the scale of the factory.

[12] Novoselov, 2011: 841
[13] The development and use of the NGI has been described in detail in recent work by Novoselov and Yaneva, 2020.
[14] Latour, 1987
[15] Akrich et al., 2002; Latour, 1987; Latour and Woolgar, 1986

In order to explore the subject of surfaces in relation to the nanoscale, this essay will take as its focus the development of 2D material technologies at the Graphene Engineering Innovation Centre (GEIC) at the University of Manchester in the United Kingdom. The essay will briefly explore the production of two materials: a 2D material membrane, which I witnessed at a stage in its development in one of the GEIC's laboratories during a five-month ethnographic study of the building in 2019; and secondly a graphene-enhanced concrete which was utilised to produce a new parking bay on a road outside of the building in 2022, described by the university as a 'living laboratory'.[16] In both of these examples, what is of concern to me is how the technologies are viewed and explored by researchers and also, eventually, the users of the technologies. This, I will show, is in part an engagement with the surface of the technologies, occurring at different scales. Through the process of scale-up, it is not possible to entirely separate the view of the 'ordinary person' and the 'scientist's' view of the surface: both must be understood simultaneously – an insight that opens up an understanding of the surface as a space of encounter.

Scaling up

In 2019, during an ethnographic study of the GEIC, I was able to witness a brief snapshot of a moment in the development of a 2D material technology in one of the ground floor laboratories of the building. These laboratories were run by university-employed application engineers, who worked collaboratively with industrial partners. This particular laboratory specialised in the development of 2D material membranes (fig. 1). The 2D material membrane which I was shown was produced not with graphene, but another 2D material, molybdenum disulphide (MOS2), and was being worked on by a member of the applications team for the laboratory named Sam,[17] who presented a series of prototypes to me and a member of the building management team, Tom.

[16] University of Manchester, 2021b
[17] Named individuals are given pseudonyms.

Figure 1 GEIC Membranes Labratory; photo taken by the author 21 January 2022

I was already aware of ongoing work on membranes within the field of nanomaterials research; a 2D material membrane, developed at the NGI in 2017, had hit the headlines with the claim that it may one day solve the world's drinking water crisis by offering an efficient means of water desalination.[18] In reports and press releases for technologies like these, however, an image of the physical membrane, produced in the laboratory, was never present. Instead, the articles would be accompanied by computer-generated images, showing hexagonal lattices between which were water and salt molecules, rendered to look almost like planets, with the sun glinting off them (fig. 2). In comparison, as I was shown the membranes in the GEIC labs, the blobs in front of me looked decidedly unimpressive. This was a sentiment echoed by Tom, who commented that the various membranes 'all look the bloody same'.[19] Sam, in response to Tom's joking dismissal of his work, took care to point out a 'particularly good one', referring to the blob's overall shape, which they proceeded to admire.[20] Yet there was some truth in Tom's joke. From our own perspectives, with the limitations of our own sight, there was little to distinguish one from another.

[18] Robinson, 2017
[19] Walking interview with Tom, 15 July 2019
[20] Walking interview with Tom, 15 July 2019

The membrane itself had been first created by an academic at the school of materials but had now travelled to the GEIC in order for the technology to be scaled up. While being worked on in the academic laboratory, only a small amount of material would be produced, and the steps taken to produce this may not be particularly efficient. Sam's task was to scale up this technology, to develop the means of producing the membrane material in large quantities – developing a 'process' which would be closer to what an industrial production facility would need to carry out. As another member of the GEIC staff told me,

> Usually the processes you do on a lab scale are not the same process that you do on a factory scale, even though you're trying to produce the same product. [...] Sometimes people think, 'oh just make the machine bigger or whatever'. I mean it's really [...] not even close to being that simple.[21]

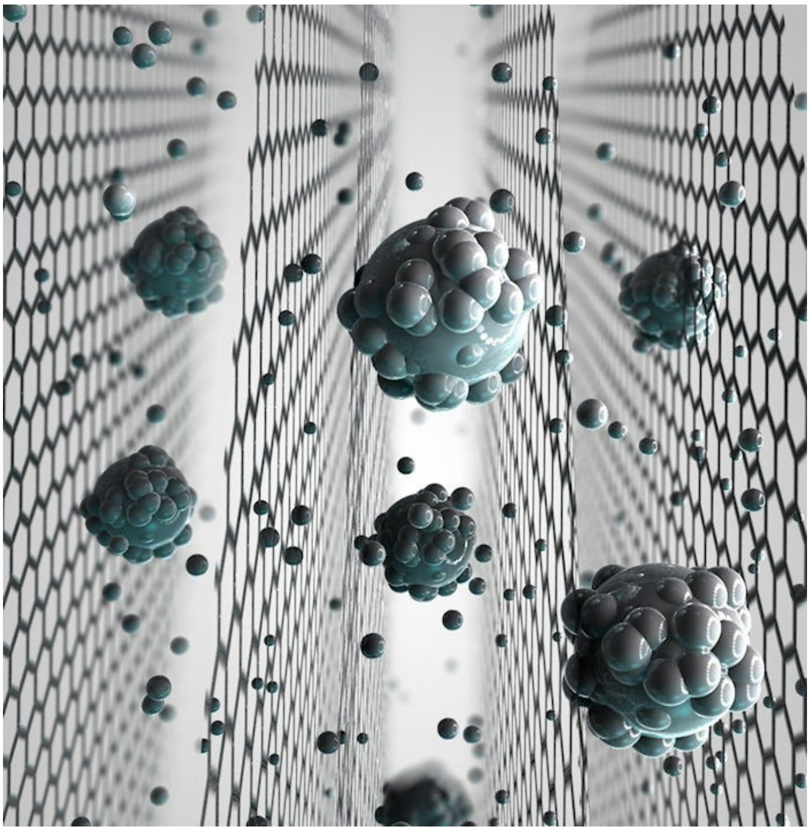

Figure 2 Visualisation of Graphene Oxide desalination Membrane. Image from Robinson, 2017. Graphenee sieve turns seawater into drinking water. The University of Manchester website

Sam was required to develop ways to produce these membranes on new systems, developing faster and more efficient steps.[22] Tom briefly explained the processes being undertaken in the laboratory.

[21] Interview with GEIC application engineer 1, 3 August 2018
[22] Interview with Sam, 21 June 2019; email exchange with Sam, 24 November 2021

> You take your 'goo' that's got your materials in, and then you force it through a substrate and then your little plates start arriving on that substrate, okay? And then you form your membrane.[23]

Pointing to some of the various pieces of machinery which surrounded us, Tom elaborated with reference to one of the membranes Sam had just produced.

> So this has gone through this rig here where we've forced it through here, and then through this [...] semi-porous membrane on here. And then we put it onto the substrate which has got a particular pore size. And then the idea is the flakes all line up, and then we end up with our flakes all higgledy-piggledy on top but all kind of essentially lying flat. Then when you put a particular liquid through, the gaps between the flakes – because the material won't go through the flakes – it has to go through the tortuous path, and that way we get filtration.

He turned to Sam:

> That's basically it, isn't it?[24]

Sam agreed. From this 'goo' that Sam began with, and after travels through various pieces of machinery, we now had in front of us a functioning membrane deposited on a substrate – in this case this substrate was nylon.[25]

Or did we? Though the blobs may 'all look the bloody same' to Tom, Sam and me, there was no way for us to know, standing over them on a work bench, whether they were truly the 'same' membranes as those produced at the School of Materials. To find out, Sam and the membranes would need to travel to another laboratory in the GEIC, known as the characterisation laboratory. Here, with the use of a scanning electron microscope, Sam was able to 'see', at the atomic scale, the topographies of the various MOS2 plates of the membrane, hidden from our view.

> I tend to use the scanning electron microscope a lot and just actually visibly looking at what the surface actually looks like.

Further tests, such as those to examine flow rates, would enable him to confirm if these really were the 'same' technology at the molecular level; without this equipment, the membranes 'might look the same'[26] but not truly be 'doing the same thing'.[27] 'Doing the same thing' in this sense meant the membrane's ability

[23] Walking interview with Tom, 15 July 2019
[24] Walking interview with Tom, 15 July 2019
[25] Walking interview with Tom, 15 July 2019
[26] Interview with Sam, 21 June 2019
[27] Interview with Sam, 21 June 2019

to engage or interact with the atoms of the substance it was meant to filter in the desired manner: whether the 2D material plates successfully created pore sizes to allow through certain atoms while excluding others. Other tests, such as tests on the technology's durability – on its resistance to denting and scratching[28] – would also be carried out. In scaling up the technology, it would simultaneously have to be modified for the kind of environments it might encounter outside of the laboratory.

The movement between the atomic scale, the 'particularly good' looking blob on the substrate, and the potential for the finished membrane to be damaged outside the laboratory complicates previous philosophical understandings of scales in relation to surfaces. No clear separation, as was suggested by Stroll, could be drawn between the respective perspectives of the 'ordinary person' and the 'scientist'. For the technology to develop, a constant oscillation can be seen between these scales: the quantity, appearance and durability of the object and its atomic make-up matter were considered alongside one another – not incompatible, but necessary points of the technology's journey between the world of the academic laboratory and the large-scale factory.

The facility as a whole was built with such movements between scales in mind. From afar, the GEIC appears simply as a middle ground between the realms of academia and industry – in interviews it was described to me as both a 'massive laboratory'[29] and a 'mini factory'[30]. Yet rather than simply becoming this stable middle ground, through the ability to access the scanning electron microscopes and other characterisation tools which allow the engineers to 'see' the world of the nanoscale, while simultaneously gaining access to machines which are able to produce technologies at a scale closer to the world of industry, the building becomes a constellation of these different worlds.

Experiments could be affected by proximity to larger scale equipment. The characterisation laboratory, containing scanning electron microscopes, required isolation from any vibrations which large scale equipment throughout the facility might create. Sam's tasks of developing a process capable of producing the membrane on a scale close to the industrial and of observing the resulting membranes at the nanoscale were both essential to the development of the technology, but the building must keep them apart. As such the floor of the characterisation laboratory was essentially separated structurally from the rest of the building and built six metres down into bedrock (Fig. 3). This is a dual

[28] Walking interview with Tom, 15 July 2019
[29] Interview with GEIC application engineer 2, 27 February 2019
[30] Interview with executive 2, 6 September 2018

challenge experienced in the GEIC, of both bringing together scales but simultaneously facilitating their continued separation. Just as the smooth surface, when magnified, may reveal much more complex topographies, in the GEIC – rather than blurring the scales of academia and industry and arriving at a point somewhere in between – a patchwork of scales could be witnessed throughout the facility, brought into relation yet kept at a distance and prevented from compromising one another.

Figure 3: VC-D flooring around the perimeter of the Characterisation Laboratory; photos taken by the author, 21 January 2022

Living Laboratory

At the side of a small road, just outside of the GEIC and deep within the University of Manchester's North Campus site, sits a patch of raw concrete, used as a parking bay (figs. 4 and 5). On its own, this concrete does not appear especially significant. Concrete is ubiquitous in the area: the North Campus, once the home of the University of Manchester Institute of Science and Technology (UMIST), was significantly developed in the late 50s and 60s as the institute expanded, and contains a plethora of concrete, modernist towers, many designed by local architectural firm Cruickshank and Seward and described by one local media outlet as 'little Brasilia'.[31] Though once the material of modernisation and progress,[32] the decaying, stained and spalled facades of these towers demonstrates that this modernist optimism has largely become decoupled from the material. The towers surrounding the GEIC, once a hub of academic activity, now stand empty, awaiting demolition. Despite the best attempts of the local modernist society, a number of professors at the Manchester School of Architecture and even some Manchester-born celebrities, the university has been reluctant to see the heritage value of these concrete monoliths, preferring to realise the monetary value of a new mixed-use development planned for the area.

But the changing reputation of concrete is not solely due to changing architectural styles, or the aesthetics of degrading concrete exteriors, but due to the ecological and environmental impacts of the use and production of concrete increasingly coming to the fore.[33] Yet, despite the huge carbon cost of its production, its use is so intrinsically connected to modernisation and development, its use has continued to expand globally.

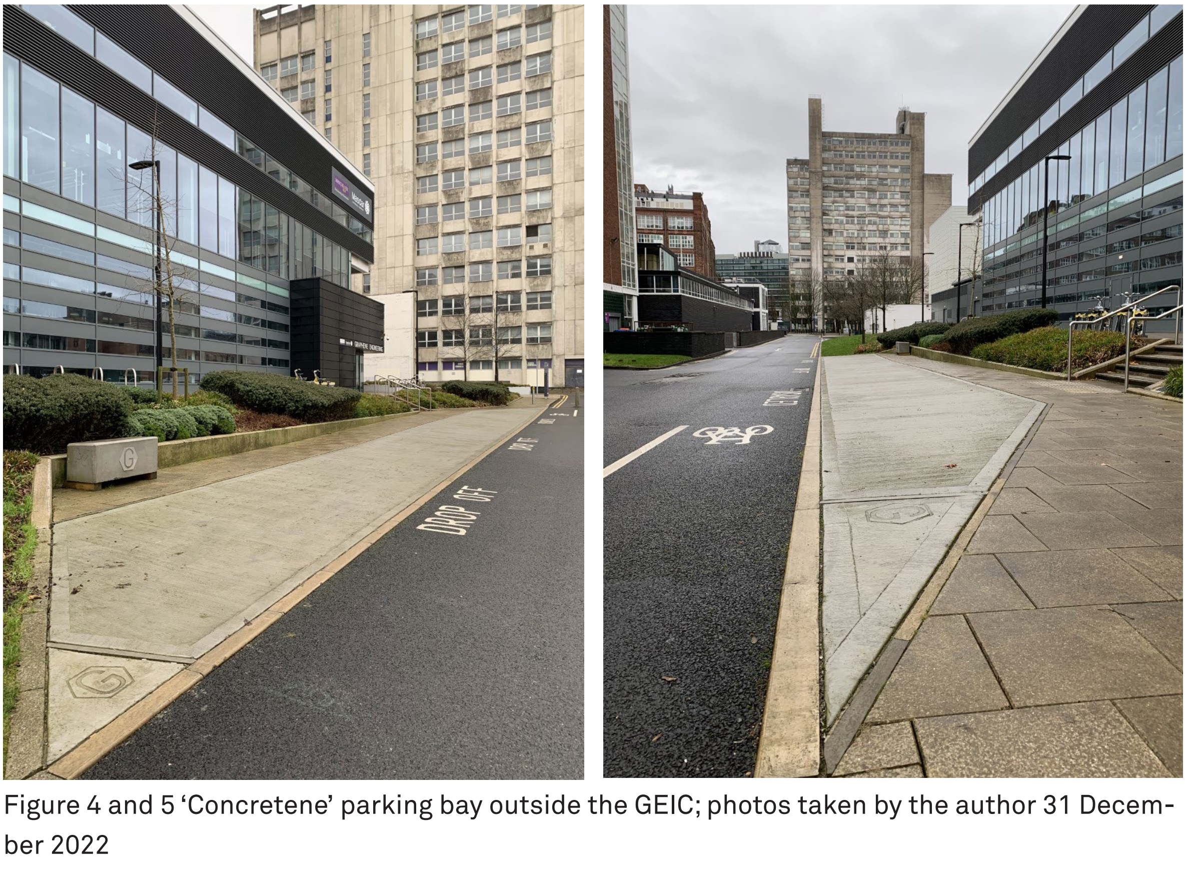

Figure 4 and 5 'Concretene' parking bay outside the GEIC; photos taken by the author 31 December 2022

[31] Schofield, 2019
[32] Forty, 2012; Minuchin, 2013
[33] Forster, 2022

It is in this context that the concrete parking bay, adjacent to the GEIC, gains significance. It is the first external test pour of a formulation of graphene enhanced concrete, branded *Concretene*, produced at the GEIC through a collaboration between the university and two external companies. It is described as a 'living laboratory', a space outside of the confines of the scientific laboratory, in which the behaviour and condition of the concrete can be observed as it becomes subject to 'real-world' conditions, coming into contact with Manchester's damp climate and the weight of parked cars and vans. In contrast to the decaying concrete found throughout the old UMIST site, this concrete is supposed to be a sign of things to come – a formulation of materials which might re-couple concrete with the fading promise of modernism.

In a press release the university hails the huge potential impact of the development of Concretene:

> Greener AND cheaper: Graphene@Manchester solves concrete's big problem [34]

The press release explains that the addition of a small amount of graphene has allowed 30% less concrete to be used and eliminated the need for steel reinforcements. It states that the impact of graphene is its ability to enhance the microscopic bonding of other elements of the concrete mix:

> Graphene makes a difference by acting as a mechanical support and as a catalyst surface for the initial hydration reaction, leading to better bonding at microscopic scale and giving the finished product improved strength, durability and corrosion resistance.[35]

The properties of the concrete are enhanced through the dispersal of these tiny sheets of graphene, which, due to their geometry, are able to provide a large surface area through which to interact with the material matrix.[36]

The university's press release claims that, if

> [r]olled out across the global building industry supply chain, the technology has the potential to shave 2% off worldwide [carbon] emissions.[37]

Despite the obvious significance of the development, the grandiose nature of the claim could, of course, be critiqued. The notion could perhaps itself be considered 'surface' level, or superficial in the sense that the complexities of con-

[34] University of Manchester, 2021b
[35] Ibid.
[36] Shamsaei et al., 2018: 656
[37] University of Manchester, 2021b

crete's environmental impact are reduced to a 'problem' which can be 'solved' through a 30% decrease in CO2 emissions. From the small patch of concrete outside the GEIC, we are invited to see an image of a future of green buildings and cities made possible through innovations established in Manchester. However, such a critique could ignore the active role of such representations in the gathering and enrolling of new allies[38] – of gaining media attention and attracting funding and potential collaborators. Such hype, and an expectation of the immanent realisation of technologies which will transform society, is a common feature of scientific advancements,[39] and the grandiose claims attached to new graphene and 2D material technologies are no different.

Returning to the site of the concretene 'living laboratory', there are few visual cues to those who have not explored the university's press releases, to indicate the significance of the development. While clearly poured far more recently than the derelict UMIST buildings, there is little to distinguish the concrete of the surrounding modernist towers with that of the parking bay. In his book *Concrete and Culture*, Adrien Forty notes the relationship between the photograph and the finished surface of concrete.

> Like a photograph a concrete structure is indexical – it carries within it direct evidence of the moment of its making. The photographic negative received light from the person, object or view to which it was exposed, giving it a direct and indissoluble link to the original subject: such is the basis of a photograph's claim to truthfulness. Likewise a work in concrete carries the direct imprint of the material within which it was cast.[40]

While the creation of many concrete structures aims to hide such traces, others have looked to accentuate them, expressing, for example, the imprints of the timber boards used to contain the poured concrete. The concretene test pour contains no such trace of its making, and, even if it were to do so, the innovation of the material lies less so in the moment of its pouring than in the formulation of its component parts. The tiny layers of graphene dispersed throughout the concrete remain entirely invisible. In this instance, an imprint has been made, after the concrete was poured, to inscribe a 'G' symbol within a hexagon (fig. 6). This slight modulation in the surface is all that would distinguish the parking bay as a space of any importance, but in doing so, the inscription aims to make 'visible' innovations imperceptible to the naked eye. The addition of graphene cannot be 'seen' by the ordinary observer; indeed, if concretene was significantly different in appearance or texture to ordinary concrete, this would perhaps

[38] Hessenbruch, 2004: 142
[39] Nowotny and Felt, 1997
[40] Forty, 2012: 254

hinder its ability to become adopted at scale outside of the laboratory. Such a mechanism of *making graphene visible* could of course not be adopted wholesale outside of the 'living lab', and if concretene is to achieve the lofty ambitions set out in its press release, it would have to be rolled out at scale – it would have to become the norm rather than the exception. Yet in this instance, as the technology begins to move outside of the laboratory, the imprinted 'G' symbol acts as a reminder, and as a *branding tool* looking to connect the material, and the GEIC, to innovation at the nanoscale and to broader technological visions.

Figure 6 'G' Graphene symbol stamped into concretene; photo taken by the author, 31 December 2022

Surface as a place of encounter

Though attempts to outline a comprehensive definition of the term 'surface' almost always appear futile, the surface is often the point at which a material or a body is able to come into contact with others: surfaces usually occur at the point at which bodies meet. As has been argued by Deleuze, a focus on the surface directs attention away from the 'true' nature of objects and entities, hidden within their depths, and towards the events swirling between them and bringing heterogeneous entities into relation:

> It is by following the border, by skirting the surface, that one passes from bodies to the incorporeal.[41]

Moments of coming together, interaction, relation and exchange are to be found at the surface.

But how easy is this surface to locate? Rather than being able to offer a contrast between the depths of bodies and the effects to be found at the surface, the surface, as seen in this essay, is *multiple*. To describe the surface as multiple, I am drawing upon the use of the term by anthropologist Annmarie Mol, whose ethnography of vascular disease explored the many, often contradictory enactments of disease, which were still able to 'hang together'. For Mol, the term 'multiple' refers to a 'manyfoldedness, but not pluralism. In the hospital *the body* (singular) is *multiple* (many).'[42] A focus on the nanoscale draws our attention to the multiple nature of surfaces and the relations formed between them: they are zones of encounter folded into one another, perhaps at times obscuring one another, at others alluding to the presence of others. In a sense, Stroll was perhaps right to distinguish the surface as viewed by 'scientists' (with the aid of high-powered microscopes) from the surface viewed and experienced by the 'ordinary person', but increasingly these views cannot be understood entirely separately. In the GEIC, these two 'views' of the surface were made possible through different laboratories, instruments and machinery. They were brought together, but only as long as they were able to maintain their separation: the production of the industrial scale could not be allowed to compromise the view of the nanoscale. Just as Sam, in developing a 2D material membrane, moved between these two 'views', this essay has attempted to show that collapsed into what at first glance might appear a mundane surface, can have within it deep worlds, new fields, new scales and technological visions of abstracted flatness that requires a branding logo to be made visible. Perhaps, as 2D nanomaterial

[41] Deleuze, 2015: 10
[42] Mol, 2002: 84

technologies become more established, as the technologies themselves become black-boxed, as they (if successful) become widely adopted components of the materials shaping the world around us, the multiplicity of the surface may recede from view. But, for now, while the novelty and promise of 2D materials is still a driving force behind their development, by following these materials, it is possible to discern a movement through this multiplicity, a movement which forms an essential part of the development process.

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“The essay allows for rich discussions of the different ways of understanding, depicting and, indeed, manipulating materials on a nanoscale.”

- Andreas Ervik, author of “A Small Old Plot,” *Metode* (2023), vol. 1 Deep Surface

“In Benjamin’s essay the surface of culture, institution, science, and the everyday becomes almost metaphorical for the meeting between graphite and concrete, and the invisible forces that make the agave both oscillate and affect.”

- Marius Moldvær, author of “I will acknowledge the Shallowness of my depth. An autoimmune, spontaneous prose essay,” *Metode* (2023), vol. 1 Deep Surface

“In social and cultural theory, Theodore Schatzki (2003, 2016) develops a flat ontology of society whose practices do not diversify into a multitude of levels, but rather take place on only one level.”

- Sybille Krämer, author of “The Cultural Technique of Flattening,” *Metode* (2023), vol. 1 Deep Surface

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