Understanding the factors influencing quality of writing and wiping for chalk and board system

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This article reports the properties of a calcium carbonate-based writing chalk prepared at the CSIR-Central Salt and Marine Chemicals Research Institute (CSIR-CSMCRI) and, further, our efforts to understand the process of writing with the chalk on two different boards. The optimum density of the chalk was found to be 1.52 g ml^{-1}, keeping in mind the careful balancing act between strength and dust-free nature of the chalk on one hand, and the ease of particle transfer onto the board on the other. Writing with the chalk yielded thin and compact appearance on a ceramic board, while that on a polymeric board was relatively broad and dispersed. Atomic force and scanning electron microscopic studies were carried out to rationalize the observation by correlating roughness on the board with the distribution of chalk particles. Wiping efficiency of the polyurethane-based duster prepared at CSIR-CSMCRI was compared with commercial duster, and the observations rationalized again with the scanning electron microscopy.

Keywords: Calcium carbonate, chalk and board system, dust production, quality of writing, wiping efficiency.

WRITING chalk has been a traditional teaching aid in educational institutions. It is likely to continue to play a critical role in education in the world, notwithstanding developments around the information technology and erasable ink for white boards. Salient aspects of writing chalk developed at CSIR-Central Salt and Marine Chemicals Research Institute (CSIR-CSMCRI), Bhavnagar have been reported earlier[1]. The article[1] describes the scale of production and cost of produced chalk sticks after discussing the relevance of dustless chalk. It is typically manufactured (in India and other developing countries) by small-scale industries with little quality control or formal product specification. Its requirement is likely to be in excess of 20,000 tonnes per annum in India, considering that there are more than 315 million students in India[2], the student : teacher ratio is 30 (ref. 3) and assuming a conservative figure of 2 kg of chalk requirement per teacher per annum. However, according to the licensee (M/s Arasan Phosphates) of the CSIR-CSMCRI 'Clean Write' dustless chalk knowhow[4], writing chalk requirement is estimated to exceed 100,000 tonnes per annum in India. This would suggest that the actual requirement per teacher is closer to 10 kg/annum on an average.

Chalk sticks are being produced in India by various crude and/or traditional methods. A century-old knowhow and general properties of chalks are discussed in a website[5], wherein dustless chalk preparation is described. A biography of the inventor of chalk is provided in another website[6], wherein experiments are described which led to the development of the first dustless chalk. Dustless chalks are made of calcium carbonate ($CaCO_3$) and a few additives, and produced by the process of extrusion; the chalk sticks appear cylindrical. Dustless chalks are compact, strong and possess high bulk density. The other variety of common writing chalk has gypsum ($CaSO_4 \cdot 2H_2O$) as the main component. Moulding technique is used for mass production of chalk sticks which appear conical. These chalk sticks have low bulk density, high void space and can easily break during handling. Preparation of classroom chalk from calcium carbonate and pastel chalk from gyspum is described in another website[7]. Chalk made of gypsum absorbs sweat (and water) from the skin of the fingers, which may lead to dryness and burning sensation; water retention capacity of gypsum is often exploited as an additive in the cement industry to enhance the settling time of concrete[8].

Generation of dust during writing and wiping is probably the most perceived shortcoming of the chalk and board combination. Students sitting near the writing board along with the instructors come regularly in contact with dust generated during writing and wiping. Many teachers and students are sensitive to it and after prolonged

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exposure, may suffer from allergy and asthma[9]. Dust production causes loss of material, cleaning and disposal problems. Recently, few attempts were made to quantify dust generation and to understand the differences between chalks made of gypsum and calcium carbonate. Majumdar and William[10] studied the nature and particle size distribution of settled dust during classroom teaching, wherein fine particulate matter capable of reaching the lungs was detected in chalk dusts. Higher amount of fine particulate matter was observed in dustless chalk over other gypsum varieties. Majumdar *et al.*[11] studied the floating chalk dust, from dustless as well as gypsum chalk using aerosol spectrometer to understand the role of particle size distribution in dust generated in classroom environment. In this study higher amount of fine particulate matter was observed with dustless chalk than with gypsum chalk. The difference between the quantity and particle size distribution between the two varieties of chalk was not significant to explain the effectiveness of dustless chalk over the gypsum variety[10,11]. Goel *et al.*[12] studied the floating dust as well as dust collected beneath the board after writing and wiping experiments for dustless and gypsum chalk using aerosol samplers, wherein the quantity of dust and particle size distribution were not significant to explain the advantages perceived with dustless chalk. Physico-chemical analyses of the chalk particles were performed to ascertain the identity of constituents and the affinity towards water. Particle morphology was correlated with aerodynamic behaviour. It was found that the nearly spherical shape of particles in dustless chalk ensures quick settling behaviour while flaky particles produced from gypsum chalk led to dust of floating nature[12]. Hydrophilic nature of gypsum chalk led to easy deposition on human skin, while hydrophobic nature of dustless chalk ensured low probability of their interaction with receptors[12].

Poor performance of chalk sticks is well known; however, organized efforts to address this problem are nearly absent in India and scientific documentation of underlying efforts performed in the west is not easily accessible. A few instruments related to writing have been developed to address dust arising from the chalk and board combination, i.e. Hand and Finger Shield[13], Writing Board[14], Chalk Board Eraser[15], and Chalk Eraser Cleaner[16]. Hand and Finger Shield is analogous to a hand glove with provision of accommodating a chalk stick[13]. Writing Board describes the preparation of a small and light board in simple and inexpensive manner using resin-type material over a base of sturdy material and roughness generation by sanding[14]. Chalk Board Eraser describes an eraser which can hold chalk sticks, and sticks to the board using attached magnets[15]. Chalk Eraser Cleaner describes a vessel covered with a mesh to remove the dust by thumping and to collect the dust generated[16]. Further, a scientific record of improved methods of chalk preparation as well as studies related to the writing process was not found upon performing a search. CSIR-CSMCRI has developed calcium carbonate-based (with the addition of a few ingredients for tuning various properties) extruded writing chalk. The preparation process was optimized to obtain chalk sticks with high bulk density, smooth finish, dust-free nature, low handling breakage, less sensitivity towards moisture, good visibility of writing and easy wiping qualities. Feedback from a few independent evaluators was obtained. In this article, we describe the preparation of these chalk sticks.

Writing board is also an important component, along with chalk stick, for better writing experience, less dusting and clear visibility. Many students possess impaired vision and face problems in appreciating (understanding) the writing on the board with poor combination of writing board and chalk in the classrooms. Generally glass (roughness enhanced), ceramic, wooden surface coated with paint and simple wall/cement are used for writing boards. Colour of a writing board is important for clear visibility of writing. Black (absorbs fully) and green (human eye is most sensitive to green colour under abundant light[17]) colours impart high contrast and are used at different places. Surface finish of a writing board depends on the material used and it governs the writing performance. Therefore, optimizing the quality of chalk to deliver good performance on all surfaces is a demanding task. Writing is a manifestation of material transfer from stick to board. The mechanism of material transfer from the tip of the chalk stick to the surface of the writing board involves sliding of the chalk stick over the surface of writing board (with normal force) and subsequent removal of material in the form of small particles which are either transferred to the writing board surface or form dust. During the process of wiping, these particles are detached from the surface of the board. The quality of writing and the dust produced strongly depend on various parameters, namely surface roughness of the writing board, properties of the chalk stick, area of contact, angle of contact, applied force during writing, etc. A recent study has reported ~50% less material loss for non-dusting chalk than that of dusting chalk, as well as ~30% less material loss for smooth writing board than that of rough writing board[10]. Further, non-dusting chalk on smooth board utilizes only one-third of the mass lost during writing with a dusting chalk on a rough board[10]. Better material utilization for dustless chalk and ceramic board has been reported in another study[12]. In this article, writing performance on rough and smooth writing boards was analysed by correlating visual macroscopic appearance to microscopic view of the material distribution. Further, correlation of visual appearance imparted by writing with surface morphology and roughness of two different boards has been studied in this article[12].

Although a few good chalk sticks were available in the market when work at CSIR-CSMCRI was initiated to develop affordable products, the formulations and manner of processing appeared to be largely proprietary, and there was scant information in the public domain on the role of different additives and their optimum concentrations. Information on the interplay between (i) chalk and board, and (ii) board and duster was also hard to obtain. We therefore undertook a systematic study while optimizing the products. This forms the basis of the present study. A detailed description on the preparation of dustless chalk along with the ingredients used and the processing method is presented herein. Effectiveness of writing and wiping is important for judging a chalk piece and to the best of our knowledge, a systematic study of writing and wiping activity between chalk and writing board is not available. An attempt to understand the process of writing is also presented. Writing appearance on two different boards is discussed in terms of fill pattern and fill factor which are correlated to the surface roughness. Particle morphology and size distribution at the chalk stick are compared with those at the board to understand the utility of the ingredients for writing. A discussion on correlation of wiping efficiency of two dusters with their microscopic texture is presented, incorporating the role of roughness of the board. Finally, a mechanism of material transfer during the writing process is presented.

Product composition and production methodology

Material composition

Basic filler (calcium carbonate $CaCO_3$: 76%): This is chosen over gypsum ($CaSO_4$) for its lower affinity towards water to reduce the sensation of dryness and burning while writing. Also, the dust generated with the chalk made up of this material has lesser probability of getting deposited in the respiratory system and better chances of getting cleared by coughing, etc. than $CaSO_4$. While $CaSO_4$ crystals are flaky, $CaCO_3$ crystals are dodecahedron, resembling spheres, and can ease the extrusion process, when extruded along with other constituents. Size of particles can play a significant role in the brightness governed by scattering and used bulk of $CaCO_3$ has an average particle size (50% integral) of 4.2 μm. Bulk supply was procured from Jaimurthy Minerals and Chemicals Pvt Ltd, Bandra, Mumbai (specification JC 404), and used without further processing.

Plasticizer (kaolinite $Al_2Si_2O_5(OH)_4$: 18%): Plasticizer was used as procured and contributed to strength and compactness leading to dust control. It also provides plasticity to the wet material, thus helping in the extrusion process. Material of the specification ‘China Clay-TSW Powder’ was procured from Suraiya Pvt Ltd, Mumbai. Bentonite was earlier attempted, but discarded after realising that the iron impurity was producing undesired colouration.

Lubricant (talc $Mg_3Si_4O_{10}(OH)_2$: 4.09%): Lubricant was added for aesthetic appeal, specifically to impart gloss and smooth surface finish. It also helps in reducing dust adherence to finger. It promotes the writing process by the mechanism of inter-laminar paste flow. It also aids in the non-sticky behaviour of chalk particles adhering to the board. Talc was procured from local market and examined for the presence of asbestos using scanning electron microscope (SEM). Fibrous objects of high aspect ratio were not observed.

Surfactant (sodium stearate: 0.46%): Surfactant was added to reduce the sensitivity towards moisture and maximize surface gloss. Higher amount leads to noticeable marks being left on the writing board, which are difficult to erase. Surfactant was purchased from National Chemicals, Vadodara.

Tap water (33–36% added as total weight of dry components): The proportion of water is the governing factor for density and extrusion pressure, and actual amount depends on atmospheric temperature and relative humidity. Lower amount hinders extrusion requiring high pressure and producing high-density chalk sticks. Further, it leads to inefficient tablet-making process and formation of micro-cracks on the surface of the chalk sticks. Higher proportion of water makes the dough soft requiring low pressure to extrude, and the wet sticks formed are unable to withstand the resistance to slide and bend. Also, it leads to release of water from the dough during extrusion, as well as prolonging the drying process.

Binder (sodium salt of carboxymethyl cellulose, Na-CMC: 1.43%): Binder was added as aqueous solution to a mixture of other dried ingredients to enhance the strength of chalk sticks and to address the dust binding. Higher amount led to poor writing experience. Other binders attempted were urea, starch, guar gum, rice starch, sodium silicate, plaster of Paris and Saresh glue flakes. Lower percentage of Na-CMC (viscosity 200–300 cP) provided effective strength to the chalk sticks produced. Na-CMC was purchased from S.D. Fine Chemicals, Vadodara.

The lack of side effects from the long-term use of $CaCO_3$ was assessed from multiple sources like the National Toxicology Programme (NTP), the International Agency for Research on Cancer (IARC), WHO (Lyon, France) and the Occupational Safety and Health Administration (OSHA) (Washington DC, USA). Calcium carbonate is used for the preparation of toothpaste and medicine (tablets). Additives present in the chalk sticks are also used in different food and healthcare products. Calcium carbonate tablets are commercially used for heartburn (antacids). Kaolinite or related silica are used in toothpaste as abrasives, often up to 50% of the constituent. Na-CMC is added at about 0.25–0.75% (w/w) into flour for baking cakes. Sodium stearate is a constituent of fat used for soap-making and is often used in the pharmaceutical industry in various mouth foams. Another feature of making improved chalk sticks involves extrusion under high pressure for compactness (strength and dust binding), which is described below.

Extrusion set-up and production process

The production process of chalk sticks involves different machines, namely weighing balance, sigma blade mixer, tablet-making machine, extrusion machine and round-channelled wooden trays. Mixing of the different ingredients is critical; however, absolute homogeneity is difficult to attain. Dry mixing of ingredients was performed for 15–20 min using a mechanical mixer (sigma blade with double-jacket water cooled) of around 18–20 kg capacity. However, the operation allows only 5–7 kg of dry ingredients to be processed. Wet mixing after addition of aqueous binder solution was carried out to maximize homogeneity of the dough using the same machine. Wet mixing of these ingredients is a slow process as water is absorbed slowly and the sigma blades are rotated at low speed (16–17 rpm) for approximately 1 h. Mixing time governs the plasticity/rheology of the dough, essential to produce soft and homogeneous dough. High rotation frequency of sigma blades leads to heat generation and faster evaporation of water, thus interfering in the dough formation which affects extrusion. This homogeneous dough is further used for tablet-making. Processed wet dough should be stored in plastic bags to curb drying or evaporation losses as it adversely affects the extrusion process.

Tablet-making and extrusion machines operate on hydraulic pressure, where the pressure cylinders used for both machines have the same diameter of 100 mm. Feeding the dough directly in the extrusion machine affects the properties of chalk, which include non-uniform strength, hairline cracks and non-uniform material transfer due to air pockets. Tablets of 100 mm diameter were produced from the homogeneous mixed dough using tablet making machine. The tablets were inserted in the cylinder of the press machine and extruded from the die (diameter 10 mm) at hydraulic pressure of around 40 kgf/cm^2. Around 450 mm long wet chalk sticks were produced, which were collected in grooves of a wooden tray placed in front of the die. Hydraulic pressure was released automatically and the die was closed with a slit after production of each stick followed by forward movement of the tray to bring the next free groove in alignment with the die automatically, with a pressure switch, cam and follower and chain mechanism. At that instant, the die was opened by the slit and another long chalk stick was extruded out, again by applying hydraulic pressure. This process with the above sequential steps was repeated for continuous production. Chalk sticks were cut into approximately 60 mm long pieces using automated mechanism, consisting of number blades installed on the rods at equal distance, mounted on top of the table carrying the trays. Vertical movement of blades was controlled by the cam and follower, and chain mechanism. Movement of the blades was synchronized with opening and closing of the die and forward movement of the tray. The chalk sticks were dried in the final stage.

The process of drying also governs the quality of the chalk sticks. It was observed that the strength and brightness of the chalk sticks increased after the drying process. The drying of chalk sticks was done in two steps: (i) shade-drying and (ii) sun-drying. Shade-drying, a gentle mode of removing water from wet chalk sticks, was applied for 6 h and after hardening of the outer portion sun drying was applied for the same duration. Drying at higher temperature reduced the time required, but the breakage percentage increased owing to formation of cracks. Finally, after complete drying process, one end of the chalk sticks was rounded by grinding operation, for enhancing the contact area with the surface of the board and making it ready to write, followed by packing.

Product specification

Density of the final product, measured by weighing a stick and determining the volume, was 1.52 g/ml. Higher density of the stick led to poor rate of mass transfer, while low density led to higher amount of dust generation along with high rate of breakage during handling. Density variation was performed by either changing the proportion of tap water or by extrusion pressure. The length of the chalk stick was kept between 5.5 and 6.5 cm to reduce the breakage during handling. The diameter of the chalk was about 10–11 mm and its shape was cylindrical, governed by the extrusion process.

Experimental

Dynamic rheological measurements were performed using a rheometer (Anton Paar, Germany), and RheowinPro 2.1 software. The measuring geometry selected for measurements was plate/plate (40 mm diameter). Viscosities at varying shear (0–1000 1/s) rate were studied at 25°C. Results are the average of three measurements.

The chalk piece was broken into suitable sizes and ground from one end (using D-150 grit paper from John Oakey and Mohan Ltd, having the grit size of around 100 μm) to reduce the thickness at approximately 2 mm for SEM study. It was subsequently dried in an oven to reduce water content and thereby enhance the image resolution. Most of the images in the study were recorded at low magnification without C or Au coating, and its absence on the images can be noticed. Leo microscope (Leo

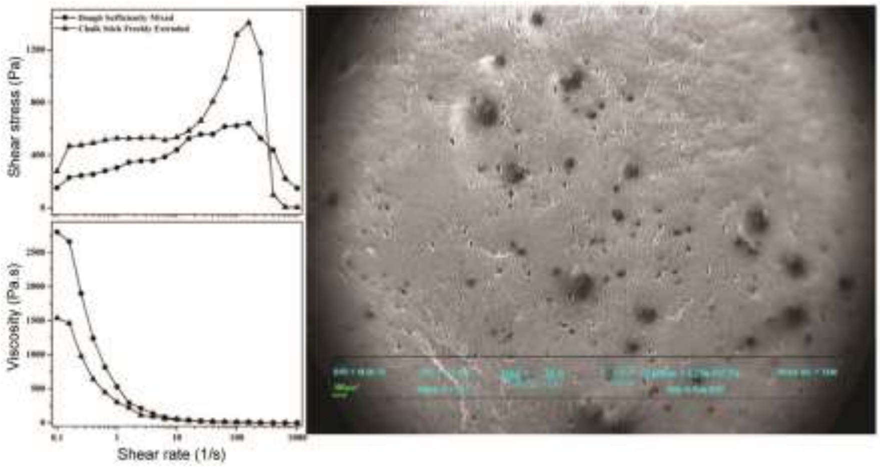

Figure 1. (Left) Graphs showing the shear stress and viscosity variation as functions of shear rate for sufficiently mixed dough and the freshly prepared chalk stick. (Right) Low-resolution SEM image of the interior surface of chalk stick exposed after breaking.

Series VP1430 Oxford Instruments) was used for SEM analysis. Green ceramic board (ceramic coated on approximately 0.3 mm steel sheet at higher than 800°C; manufactured by Hakim Displays, Vadodara) and green polymer board (writing-grade hard melamine coated on mica, probably during polymerization; manufactured by Scholar Art, Indore) were procured from locally available commercial sources. The ceramic board felt smooth upon touching, while polymer board felt rough. Chalk coverage on the boards was determined by capturing images through an optical microscope. Surface roughness of the boards was acquired for area of 50 μm × 50 μm in semi-contact mode taking 256 steps in both dimensions using the NTEGRA AURA (NT MDT) scanning probe microscope. Surface morphology of the boards was acquired by SEM images to corroborate the atomic force microscope (AFM) images.

Results and discussion

Snapshots of chalk production process

Non-Newtonian flow behaviour of the dough was studied to understand the influence of pressure during extrusion. Figure 1 shows graphs of dynamic viscosity and shear stress with the shear rate, for sufficiently mixed dough and freshly extruded wet chalk stick. Both the samples showed shear thinning behaviour as viscosity decreased upon increasing the shear rate. This indicates enhanced flow under applied shear, implying easy extrusion at higher force. The sufficiently mixed dough showed lower shear-thinning and higher viscosity than that of the chalk stick, under applied shear rate. Softening induced by tablet-making and extrusion process might be due to compaction of raw dough under pressure, which can lead to reduced material discontinuity by removal of air pockets and can also induce further elasticity. Insufficiently mixed dough samples showed brittle behaviour, and their rheology could not be studied as these came out from the measuring geometry under applied shear.

Figure 1 also shows an electron microscope image of the internal surface, exposed by breaking, from a representative dried chalk stick. Compactness in the chalk stick can be observed where only small voids, of the order of 100 μm, are seen, which are presumably formed by removal of water during evaporation.

Material transfer during writing

Size and morphology of particulates in the chalk stick were studied by electron microscope as a first step to understand the process of writing. Physical appearance of major constituents of chalk was compared in their powder form and in the stick prepared. Figure 2 shows electron microscopic images of chalk stick surface and powders (used bulk) of $CaCO_3$, kaolin and talc, at a magnification of 4000×. Images of the same set of objects at higher resolution (20,000×) are shown in Figure S1 (see Supplementary Material online). $CaCO_3$ powder contains a continuous size distribution of crystals whose shape is a combination of scalenohedron and rhombohedron[18] having size of a few hundred nanometres[18]. These in turn form nanometer-sized agglomerates. Crystals and agglomerates, similar in shape and morphology to that in $CaCO_3$, are abundant in chalk stick. Kaolinite particles are loosely bound agglomerates of small flakes and these particles are also visible in chalk sticks. Talc particles are much larger than the other two constituents and sheet-like packing can be observed. Distinct talc particles are not visible in chalk stick, probably due to small percentage and facile breakage of slippery sheets. Effective performance of an ingredient in small amounts can be realized upon efficient mixing.

To summarize the discussion, visual comparison of particle morphologies of the constituents with the chalk

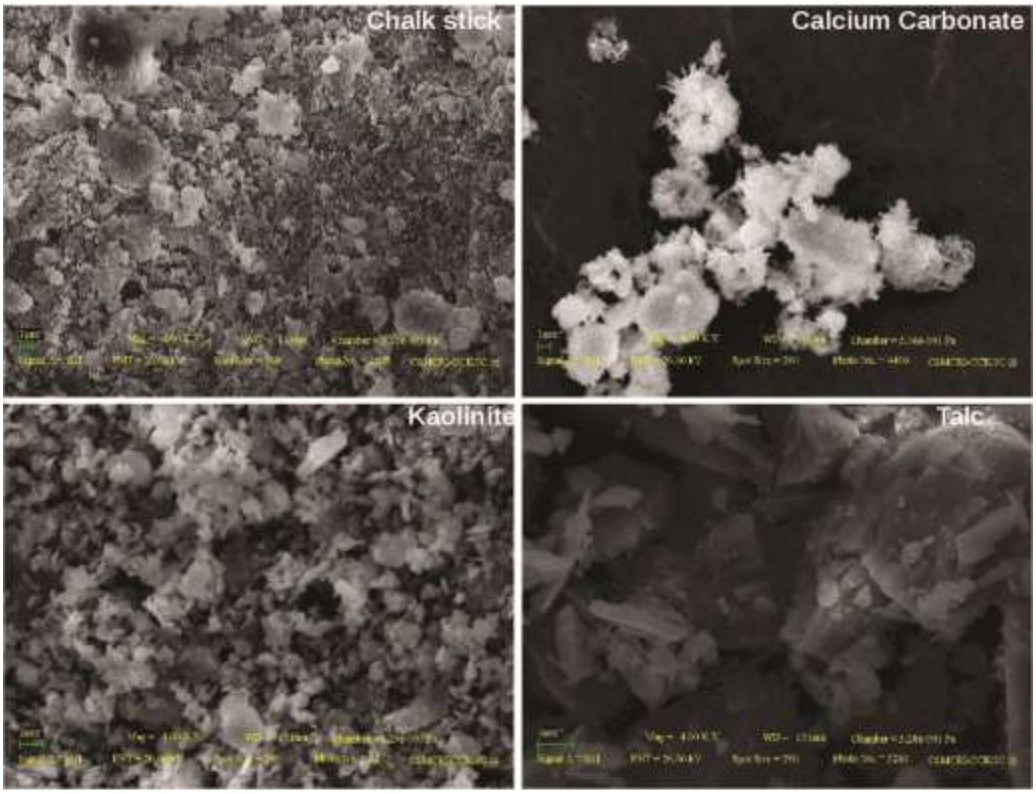

Figure 2. SEM images of the chalk stick surface and powders of solid constituents, i.e. $CaCO_3$, kaolinite and talc at a uniform magnification factor of 4000.

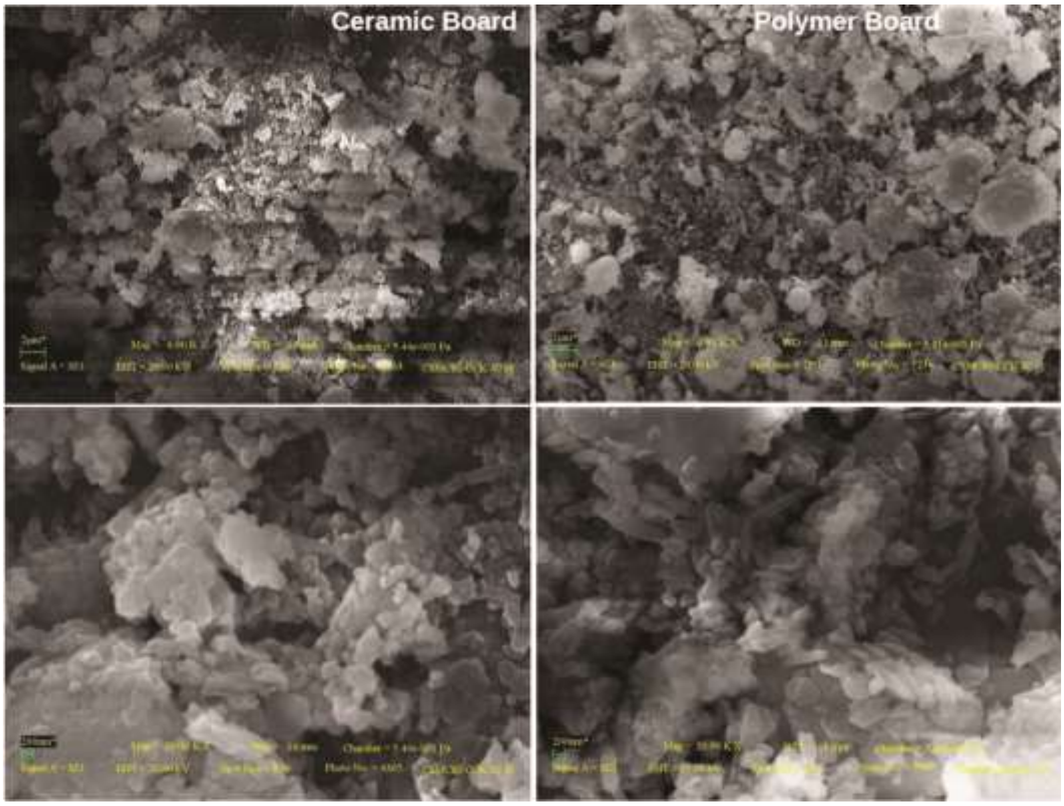

Figure 3. SEM images of chalk writing etched on ceramic (left panel) and resin board (right panel) surface. Top row images are acquired at magnification factor of 4000, while bottom row images are acquired at magnification factor of 20,000.

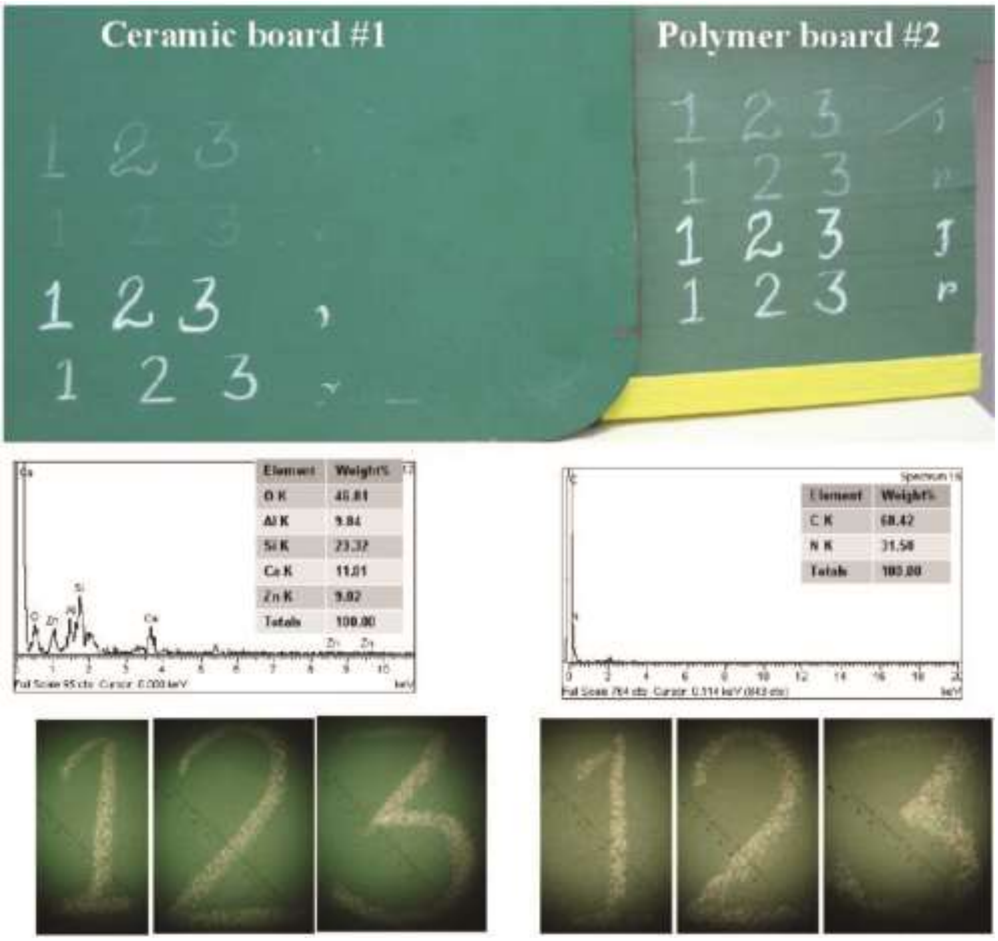

Figure 4. Writing performance on two boards, shown in the top image, captured through a camera from a distance of ~1 ft. Numbers 1–3 are written in separate rows and a set of rows is erased to understand the ease of wiping. EDAX profiles of the respective boards and the magnified view, through optical microscope, of numbers written on them are shown in the middle and bottom rows respectively.

stick indicates lumping as well as compaction of calcium carbonate and kaolin. Aspect ratio of crystals of $CaCO_3$ and kaolin is reduced in chalk sticks and spherical morphologies are generated. Talc particles may have broken to the extent of being indistinguishable from kaolin and $CaCO_3$ particles. Physical treatments of mixing by machines and extrusion are the likely causes of morphology alteration of particles and compaction into lumps.

Chalk particles transferred on two different boards were examined through electron microscope to understand the material transferred during writing. Green ceramic and polymer boards were etched with chalk and is observed at high resolution under an electron microscope (Figure 3). The particle distributions in both cases are not distinguishable from the chalk stick, as shown in Figure 2, suggesting utility of all constituents for writing. Polydispersity of particles leads to good writing performance by higher fill factor and homogeneous coverage of the surface. Small crystallites of the order of 100 nm size are invisible to the human eye (bacteria and virus cells are of this dimension) while the micron-sized agglomerates are visible, and writing enhancement by the former is achieved by filling of voids between the micron-sized agglomerates. Enhanced visibility can also be realized by spherical morphology of particles in our preparation compared to chalk particles made up of gypsum with flaky crystals. Spherical morphologies of the constituent particles lead to higher proportion of light undergoing multiple reflections/scattering, eventually leading to diffused reflection of the light beam. Glare of the writing boards can be partially addressed by this mechanism.

In order to understand the process of writing, we correlated the appearance of writing on two different types of boards, green ceramic board and polymer board, to the roughness of the boards. Few letters were written on the two boards by applying normal force and captured through a camera. High-resolution images were also obtained using optical microscope to observe smoothness, continuity, and fill factor of the writing. Figure 4 compares the direct appearance of a few letters written on ceramic board and polymer board. The writing on the ceramic board appears thin (sufficient to visualize) and

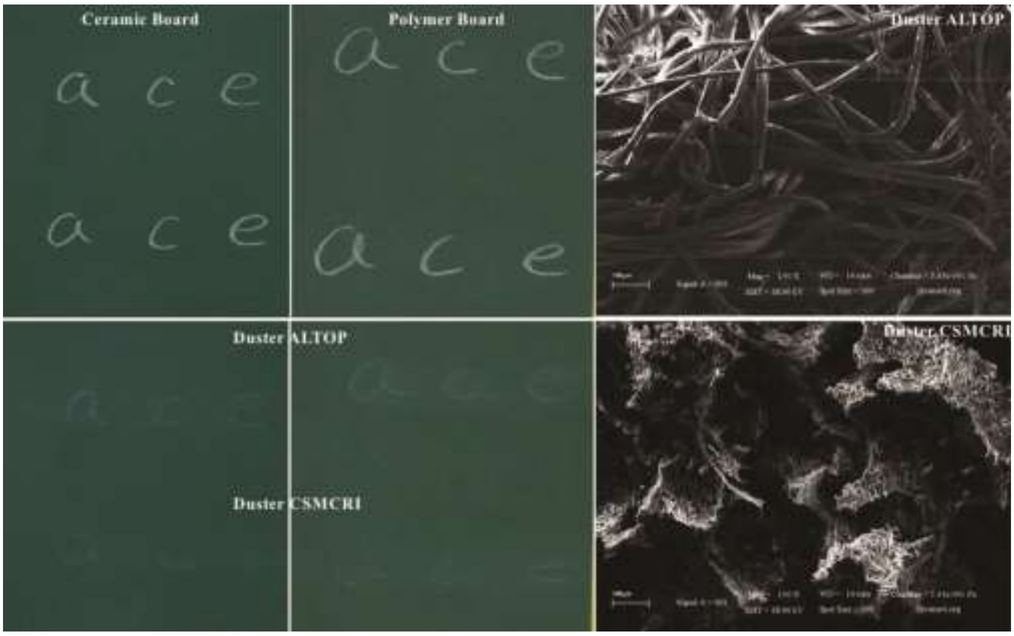

Figure 5. Wiping experiment on ceramic (left column) and polymer (middle column) boards using commercially available ALTOP duster (text at the top line) and home-made polyurethane duster (text at the bottom line). SEM images of the dusters are shown in the third column: (top, ALTOP; bottom, CSIR-CSMCRI).

with uniform distribution of chalk particles, while that on the polymer board is thicker and diffused/dispersed. Figure 4 also shows the optical microscope view of letters written on ceramic board and polymer board. Higher fill factor and homogeneous coverage for the green ceramic board is observed, which may be the reason for better visual appearance. Elemental composition of the surface coatings of the ceramic and polymer boards were also determined, and the EDAX data are shown for reference below the pictures of the corresponding boards. Ceramic board showed presence of various metallic elements (Al, Ca, Zn), Si and O, while the polymer board showed presence of C and N only.

Wiping of chalk particles is also an important criterion of quality and is governed by the board surfaces. Commercially available dusters are of fibrous material and an attempt was made to prepare a duster of porous matrix using polyurethane as the medium. Few letters were written on two different boards and wiped using a typical commercial duster (ALTOP) as well as a homemade polyurethane duster (labelled CSMCRI), at normal force and a single to and fro motion, as shown in Figure 5. The figure also shows electron microscope images of representative samples of the two dusters. The CSMCRI duster showed a more effective wiping performance than the ALTOP duster. This may be due to the difference in their response under abrasion force. Three-dimensional nature of the abrasive surface for CSMCRI duster can lead to more contact during rubbing, while the agglomerates of one-dimensional fibres, as in ALTOP duster, can offer much higher displacement upon application of force leading to less effective wiping. Writing on the ceramic board was easier to wipe than that on the polymer board, suggesting the role of surface morphology of the board.

Surface morphologies of the ceramic and polymer boards were observed through AFM as well as electron microscopy to understand the difference in writing appearance. Figure 6 shows a comparison of the surface morphologies. Average roughness (Sa), surface skewness (Ssk), and root mean square gradient (Sdq) for AFM images of ceramic board were 98.7 nm, 0.308 and 0.0593 respectively, while the corresponding numbers for the polymer board were 1486 nm, 0.682 and 0.295 respectively. The ceramic board possesses uniform spread of low-amplitude variation of surface and the polymer board contains sparse appearance of high-amplitude variation of surface as shown on the left and right side of Figure 6 respectively, where the top and middle panels show the high-resolution AFM and SEM images of the two surfaces. Low-magnification electron microscope images indicate prominence of secondary roughness (low frequency occurrence of periodic structure) in the polymer board, while the ceramic board does not possess such long-range roughness (Figure 6, bottom panel). Sparse occurrence of roughness in the polymer board explains non-uniform spread of chalk particles and high amplitude of roughness leads to deep percolation of particles (or large chunks of particles are cut) in the board producing marks which are difficult to erase by wiping. The exercise of wiping performed on the two boards suggests efficient wiping on the ceramic board, while noticeable marks on the polymer board are erased to a (far) lesser extent (Figure 5). Surface roughness was sampled at a few locations for each

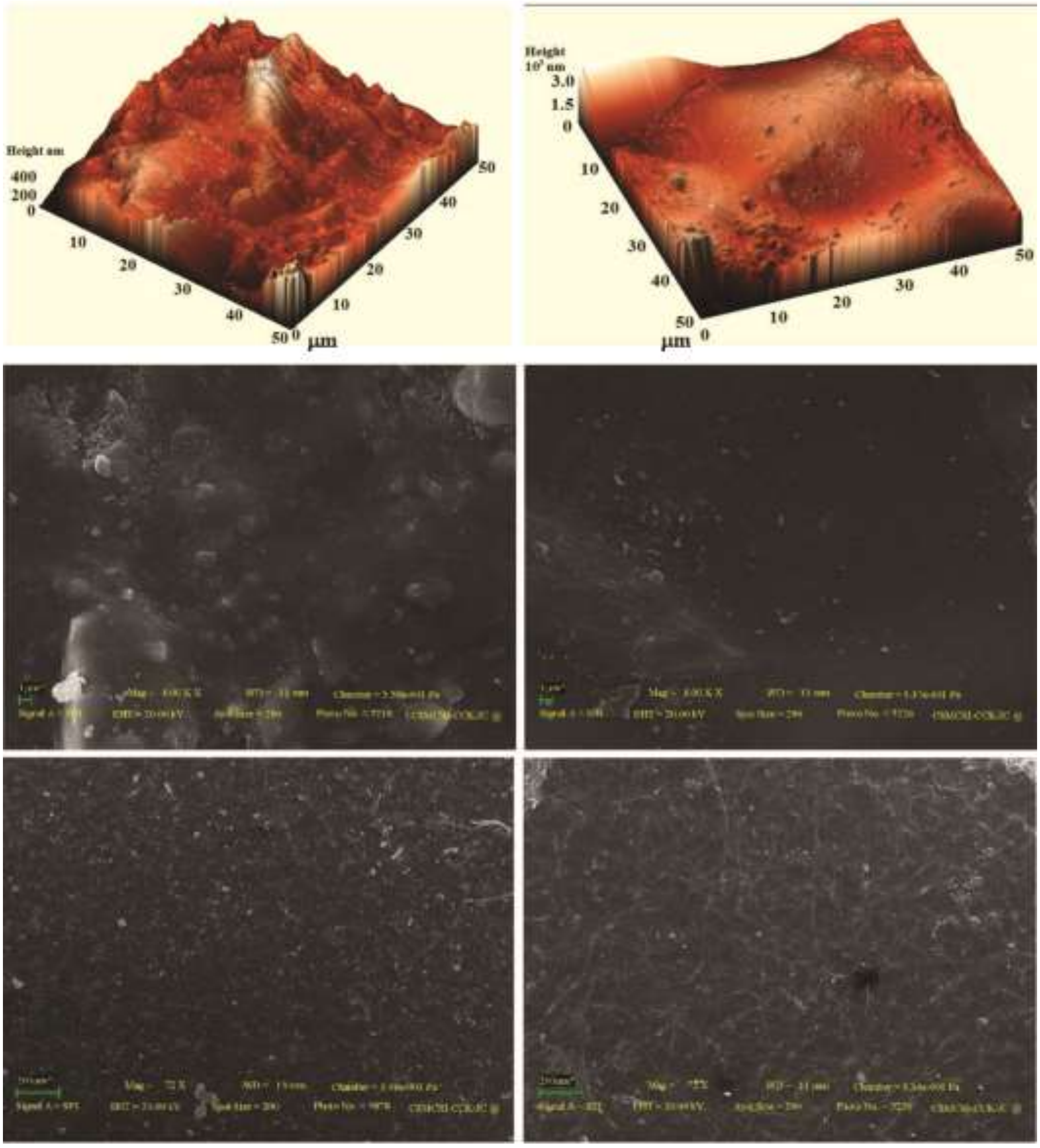

Figure 6. Surface topographies of ceramic (left column) and polymer (right column) boards. Top panel compares the topology observed through atomic force microscope. Middle and bottom panels compare the electron microscope images obtained at higher and lower resolution respectively.

writing board and AFM images from few locations for the two boards are given in Figure S2 (see Supplementary Material online).

Mechanism of material transfer during writing

The different aspects of mechanism of material transfer during writing are important from the point of visibility of writing, easy wiping, dust generated, feel of writing, etc. An engineering perspective of the process of writing is imperative as it involves removal of particles from the tip of chalk stick by wear (cutting) and simultaneously their adhesion to the surface of the board. The chalk stick slides on the surface of the board and material gets transferred in the form of layer which appears as writing in the form of lines due to adhesion[19]. In the process of writing, the material from the tip of the chalk stick is removed due to both abrasive as well as adhesive wear. Due to normal load on the chalk stick and surface energy of the writing board, the material gets transferred from the chalk stick to the board in the form of small particles as the adhesion arises from molecular forces between the surfaces[20]. The asperities on the board surface remove material more effectively from the tip of the moving chalk stick (micro-cutting).

The process of adhesion occurs when two surfaces are pressed together, either under normal force (load) or under combined action of normal and shear forces, which

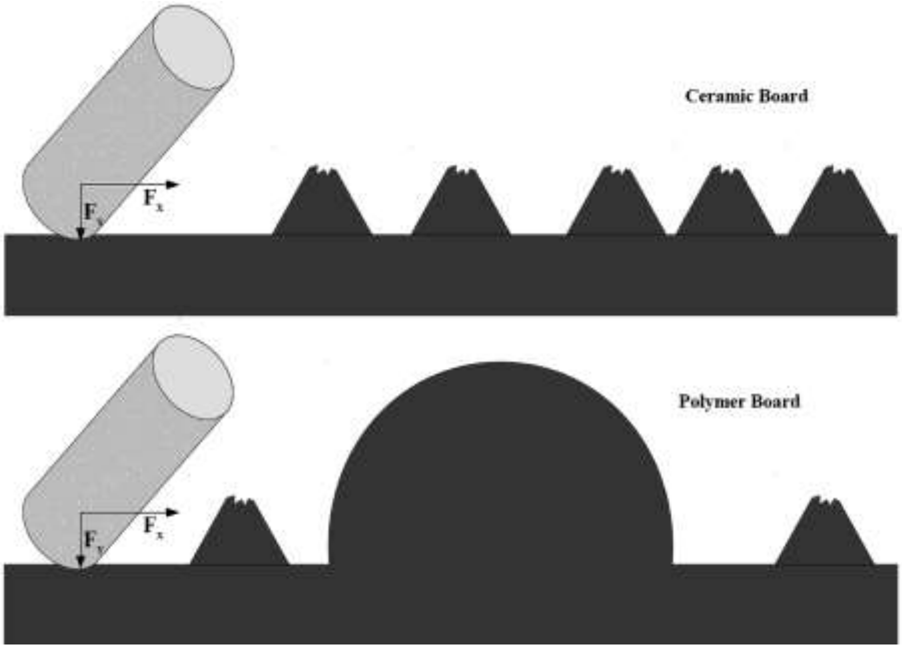

Figure 7. Roughness model on the two boards studied. Uniformly spread and densely populated asperities are shown in ceramic board (top), while the polymer board (bottom) possesses sparsely located roughness. Polymer board also possesses abundance of surface waviness, which is described by a large hemisphere.

results in friction and wear[20]. Adhesion is considered to be either physical or chemical in nature[21]. After detachment from the tip of the chalk stick, chalk particles come in contact with the surface of the board, enhanced by the asperities, and adhesion is realized by the physical interaction of van der Waals forces[20].

The chalk particles removed due to micro-cutting are partly used to fill the valleys and excess (in amount or size) particles fall down near the board or get suspended in air. The ratio of material transfer to the board or dust generation may change depending upon the combination of chalk stick and board surface. This explains the higher mass loss for the rough board than for the smooth board for a given chalk[10]. Figure 6 critically examines the surface topography of both surfaces. It can be observed that the polymer board surface shows waviness with undersize asperities and valleys, while on the ceramic board surface, along with waviness, asperities (peaks) and valleys are dominantly present. These asperities and valleys cut the material from the chalk stick and accumulate (hold) it on the surface respectively. Figure 7 is a schematic describing these differences on the two boards. As a combined effect on the ceramic board surface the chalk material distribution is evenly spread, as can be seen in Figure 4, while sparse and random distribution can be observed on the polymer board. The asperities on the surface help to increase the friction which leads to more effective transfer of material from chalk to board and also continuous distribution of material leading to compact lines. The waviness of the surface with low surface roughness results in non-uniformity in material transfer and non-continuous lines in writing which can be experienced while writing on a rough stone surface, and in such surfaces abrasive wear is the dominant contributor. In the case of smooth surface (low amplitude roughness with low waviness), the adhesive wear mechanism dominates due to increase in effective area of contact and additionally, the small asperities also remove material by micro-cutting. Low roughness of surface decreases the effectiveness of writing, though the real area of contact increases but the particles do not have sufficient physical contact area (interlocking between surface roughness and particles) for cutting to take place. Thus, for effective writing with minimum dust production, optimum surface roughness that is homogeneously spread is required. Homogeneous distribution of asperities and valleys on the surface will render smooth writing appearance.

In addition to the quality of writing, roughness of the writing board also governs production of dust particles during wiping. The higher surface roughness leads to thicker writing layer compared to smooth surface, which on detachment during wiping produces higher proportion of dust. Thus, surface roughness of the writing board governs better writing (visibility) and low dusting during writing as well as wiping.

Conclusion

Preparation of chalk sticks has been modernized in this study for making it relevant to contemporary times.

Taking calcium carbonate as the base material, various additives were mixed to optimize the desired attributes. The process of mixing and extrusion was performed for enhancing the strength to the level of optimized writing performance. Detailed documentation of the process is provided here.

The process of writing was analysed in terms of material transfer of particles from chalk stick to board. Distribution and morphology of the particle on the stick were compared to that of the writing etched on the surface to address the utility of the constituents. Roughness on board surfaces was correlated to the writing appearance. Transfer of particles during writing was analysed in terms of abrasion (cutting and grinding) and adhesion to the surface. Factors governing writing appearance and material loss through dust generation have also been discussed in this article.

Conflict of interest: The authors declare that they have no conflict of interest.

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Corrigendum

Protocols for riverine wetland mapping and classification using remote sensing and GIS

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The reference of the book by Kar (2013) may be replaced by the following original reference:

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